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DEPARTMENT OF THE NAVY OFFICE OF NAVAL RESEARCH FAR EAST  
DEPARTMENT OF THE AIR FORCE OFFICE OF SCIENTIFIC RESEARCH FAR EAST  
UNITED STATES ARMY RESEARCH OFFICE FAR EAST

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### Achieving Universal Peace

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A New Era Dawns

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Synthetic diamond crystals  
Reynolds-averaged Navier/Stokes method  
Direct simulation  
Statistical modeling of turbulence  
Chemical texturing  
Sputtered longitudinal recording disks  
Thermal spraying  
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Vapor phase coating processes  
Space Technology Research & Development  
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Science Council of Japan  
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Si-Ge heterostructures  
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Japan New Diamond Forum  
High pressure synthesis  
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Diamond applications  
Cubic boron nitride  
Turbulence research  
Large eddy simulation  
Magnetic recording disks  
Perpendicular recording disks  
Surface engineering  
Coating structure  
Low-pressure laser spraying  
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Cover: Hirohito, the Emperor of Japan, died at age 87 on January 7, 1989 at 6:33 a.m. His era, the 64-year Showa Era, the longest reign in Japanese history, was a period of war, development, and prosperity. Showa--"Age of Enlightenment and Harmony"--now becomes his name: Emperor Showa. The Cabinet approved the name Heisei--"Achieving Peace"--for the reign of the eldest son, Akihito, 55, the 125th emperor of Japan. Emperor Akihito signed with a calligraphy brush to make it official. The new era began on Sunday, January 8, and this year is Heisei 1. The word Heisei, formed of two Chinese characters, is the choice for this cover of the Scientific Information Bulletin. The calligraphy was composed and contributed by Jeannie Chen, the wife of Dr. Edward S. Chen, associate director of the Office.

# THE 1988 KYOTO PRIZES

Sandy Kawano

**T**he 1988 Kyoto Prizes were awarded to Dr. John McCarthy, the "father" of artificial intelligence; Dr. Noam Avram Chomsky, for his "Generative Grammar Theory," which revolutionized the study of linguistics; and Dr. Paul Thieme, for his outstanding contributions to the field of Indology.

On 10 November 1988 the fourth annual presentation ceremony for the Kyoto Prizes was held at the Kyoto International Conference Hall. The Laureates honored at this ceremony were Dr. John McCarthy, Dr. Noam Avram Chomsky, and Dr. Paul Thieme.

The Kyoto Prizes have been awarded annually since 1985 by the Inamori Foundation to honor some of those people who have contributed significantly to the scientific, cultural, and spiritual development of mankind. Each year specific fields from the general categories of Advanced Technology, Basic Sciences, and Creative Arts and Moral Sciences are selected. This year's fields are Computer Science and Engineering (Artificial Intelligence), Cognitive Science, and Philosophy/History of Ideas (Ancient Indian and Greek).

Dr. John McCarthy, a pioneer in the research of artificial intelligence (AI), is the Laureate in Advanced Technology. Since the inception of AI, Dr. McCarthy has challenged the basic problems of this field and has earned the title "father of artificial intelligence."

Dr. McCarthy entered the California Institute of Technology at the age of 16 and quickly became interested in AI research. Among his colleagues at Princeton University, where he obtained his Doctor in Mathematics, was Dr. Marvin Minsky. These two young researchers later became the two greatest authorities on AI. Dr. McCarthy's earliest research focused on AI based on automaton; he was coeditor with Dr. C.E. Shannon of a publication titled *Automata Studies*. This book had a great influence on the automaton studies conducted in Japan.

One of Dr. McCarthy's achievements is the study of "common sense reasoning," in which the logic of common sense reasoning is formalized to provide reasoning capabilities to computers equal to that of humans. From the study of "Programs with Common Sense" in the 1960s to the recent "Circumscription--A Form of Non-Monotonic Reasoning," Dr. McCarthy has consistently proposed new theories beyond the scope of the conventional inference of information science, contributing to the development of this field.

His most outstanding work, however, may be the creation of LISP, a programming language for symbolic processing. Conventional programming languages were designed for numerical processing, while LISP was based on the idea of what functions are required for effective symbolic processing. Most of the current AI research uses LISP. Dr. McCarthy's concept significantly influenced the present

programming languages and is considered to be the greatest invention in the field of computer science in this century.

In the field of computer engineering, Dr. McCarthy proposed the basic concept of the time sharing system and was involved in its production. This opened the door toward the development of the present large computers.

In addition to these academic achievements, Dr. McCarthy started the first AI project at the Massachusetts Institute of Technology in 1958 and established the Artificial Intelligence Laboratory. After moving to Stanford University, he also established the AI Laboratory there. While president of the American Association for Artificial Intelligence from 1983-84 he contributed to the instruction of younger researchers and to the development of the association. Dr. McCarthy was awarded the 1971 A.M. Turing Award and the first Research Excellence Award of the International Joint Conference on Artificial Intelligence in 1985.

The outstanding achievement of Dr. Noam Avram Chomsky, the Laureate in Basic Sciences, lies in his proposal of "Generative Grammar Theory," which marked the beginning of a major revolution in linguistics. In this theory he provided an ambitious program to explain the structure of the human mind.

Linguistics before Dr. Chomsky was limited to the study of the particular structures of individual languages by means of factual description and classification and failed to take up the question of linguistic universality. It was thought that language was acquired behaviorally through external experience, and the essential structure behind it has been ignored. Dr. Chomsky perceived that all human languages share

general principles on a deep level in spite of their superficial disparity and diversity. This universality lies deep in human specific nature and is inherent in all humans. In view of this point, Dr. Chomsky postulates that the essential understanding of not only linguistic structure but also human mental processes, namely the structure of human inherent and universal reason, can be accomplished through the research of common linguistic rules.

Dr. Chomsky's "Generative Grammar Theory" is based on the above conceptions. It focuses on syntactic rule in a dynamic manner as a rule of structure for generating sentences, which caused a major revolution in linguistics. In addition, Dr. Chomsky formulated this "Generative Grammar Theory" to a precise mathematical theory with a symbolic system. The theory itself became the basis for the theory of automata and mathematical linguistics and has since provided the basic support for the development of information science, especially computer science.

Dr. Chomsky's theory has not only influenced linguistics and information science but has also encouraged the formation of cognitive science by providing its basis. Moreover, it has deeply influenced philosophy and has generated a substantial flow of contemporary ideas.

Dr. Chomsky is currently a professor at the Massachusetts Institute of Technology, where he is vigorously engaged in research and is still at the forefront of his field. By refining and extending his general theory, Dr. Chomsky has recently proposed the "Parameter Theory," which explains the grammatical differences between common universal structure and various languages.

Dr. Chomsky is also well known as a sincere intellectual who promotes peace from the standpoint of humanism. His theoretical system is an outstanding monument of 20th century sciences and ideas. He is a scientist who can justly lay claim to the title of "intellectual giant of the 20th century."

Few scholars have contributed as much to the field of Indology as Dr. Paul Thieme, the 1988 Kyoto Prize Laureate in Creative Arts and Moral Sciences. His extensive philological studies have added immensely to our knowledge of classical Indian literature and provided a solid foundation for the study of Indian history of ideas, and the many outstanding scholars he has trained attest to his exceptional abilities as an educator.

Starting with a thorough grounding in the Western classics and Indo-European comparative linguistics, Dr. Thieme has directed his efforts primarily to the study of Indo-Aryan literature, where his contributions have earned him recognition as one of the most distinguished successors to the tradition of Indology in Europe. He has specialized in two principal areas. One area has been the philological study of Vedic, the most ancient of the Indo-Aryan languages, in conjunction with the linguistic and interpretative analysis of the great Vedic text, the *Rig-Veda*. The other area has been the elucidation of the indigenous Indian grammar, the origin of which traces back to several centuries B.C. Although Dr. Thieme has focused his efforts on these two specialties, which are considered the most difficult in Indian classics, his many achievements attest to his wide interest in the entirety of Indian culture, from philosophy to religion to literature.

One of Dr. Thieme's projects, begun in the early days of his career, has been his ongoing research on "Wortkunde" detailing the meaning of various important Sanskrit words and concepts. The German term "Wortkunde," indicating the study of the meaning of words, is applied in the field of Indology to a linguistic method developed early in this century by the eminent Vedic scholar H. Oldenberg. In this method, important words in the history of religion, ideas, and culture are subjected to a process of close examination in order to avoid both the limitations of traditional textual readings and the prejudices of modern philology. Examples of a particular word's usages are assembled from the entire field of Vedic literature, arranged and analyzed according to context, investigated for basic and central meanings, traced for subsequent etymological development, and examined in light of their Indo-European roots. Using this method, Dr. Thieme clarified the meanings of numerous important terms, including "ārya," the Aryans' poetic name for their own race, "brahman," the supreme principle of the universe and one of the fundamental axioms of Indian philosophy and religion, and "pūjā," a primary concept in Hindu spirituality and worship. Dr. Thieme's investigation of such basic concepts via this meticulous method has pioneered new territory in his field and provided it with a solid theoretical grounding.

From among the ranks of Dr. Thieme's students have emerged many leading scholars in Vedic studies, grammar, Indian philosophy, the middle period Indo-Aryan philology, and Indo-Iranian studies, providing further evidence of his profound and lasting influence on his profession.

The world today is seeking progress not only in scientific disciplines but also in the realms of ideas and culture. In the pages of the classics we find humanity's response to the universal questions common to all ages; to clarify the meaning of these works is therefore to illuminate the very nature of mankind. The achievements of Dr. Thieme in this field deserve the highest praise.

*Sandy Kawano is the editor of the Scientific Information Bulletin. Before coming to Japan, she worked for the Naval Civil Engineering Laboratory, Port Hueneme, CA, as a technical writer-editor. She has a Bachelor of Arts degree in Liberal Studies from California State University, Northridge.*

# TREND OF SCIENCE IN JAPAN

Jiro Kondo

**T***his article provides a brief summary of the Science Council of Japan (JSC) and presents selected results of a recently completed activity by the JSC on a survey of trends in science in Japan and the outlook for the future from a Japanese perspective.*

## INTRODUCTION

The Science Council of Japan (JSC) was established in 1949 as an organization representing the scientists of this country both internally and internationally. JSC is organized as shown in Figure 1. There are about 450,000 qualified scientists who belong to academic societies. As of July 1985, 739 societies were registered at JSC. Over the last 3 years these figures have increased to 470,000 and 840, respectively.

Science or "kagaku" in Japanese is defined as the intellectual and creative activities of human beings, including humanities, social sciences, law and political sciences, agronomics, engineering sciences, and medical sciences as well as natural science. The 210 members of the JSC represent 71 groups of disciplines that are classified into 7 divisions, as indicated in Figure 2 and Table 1.

The 180 Research Liaison Committees (RLC), working as the national committees to the respective international unions, coordinate the activities of Japanese scientists and academic societies and examine future plans for certain specialized field of sciences. Usually 10 to

30 members of every committee, a total of 2,300, are nominated by the respective academic societies. Senior scientists belonging to the RLC work together with members of the RLC. They are associate members of the JSC.

## TREND OF SCIENCE IN JAPAN

In order to gain a perspective and to identify topics for a long-term range planning for science, the research and analysis have been conducted by the Third Standing Committee (Chairman Dr. Y. Yasoshima) since 1985.

A survey was conducted among the 2,000 members and associate members of JSC and 840 academic societies to determine the trend of research subjects, present status of research activities, the level of research compared with the international standard, and impediments to the progress of science. In Figures 3 and 4, (a) represents the results of the survey for scientists and (b) represents the results for academic societies.

The 180 Research Liaison Committees analyzed the results of the survey, then reports on the trend of science in the 71 groups of disciplines were completed by members of JSC. Members of each of the 7 divisions prepared reports for their respective division. Finally, the Third Standing Committee finished the General Theory, which consists of six sections as follows:

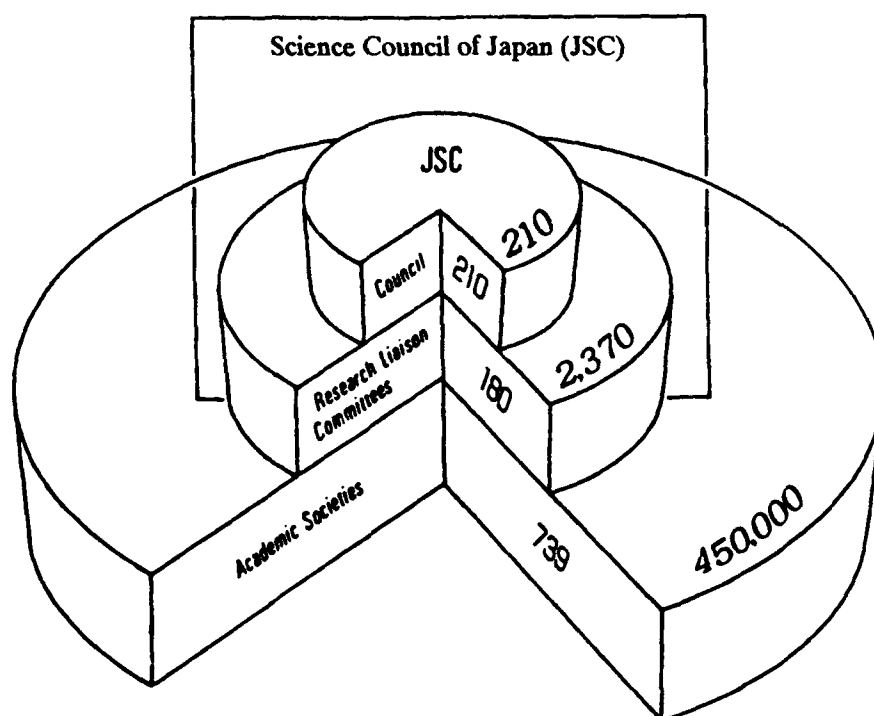


Figure 1. Science Council of Japan as a representative body of scientists.

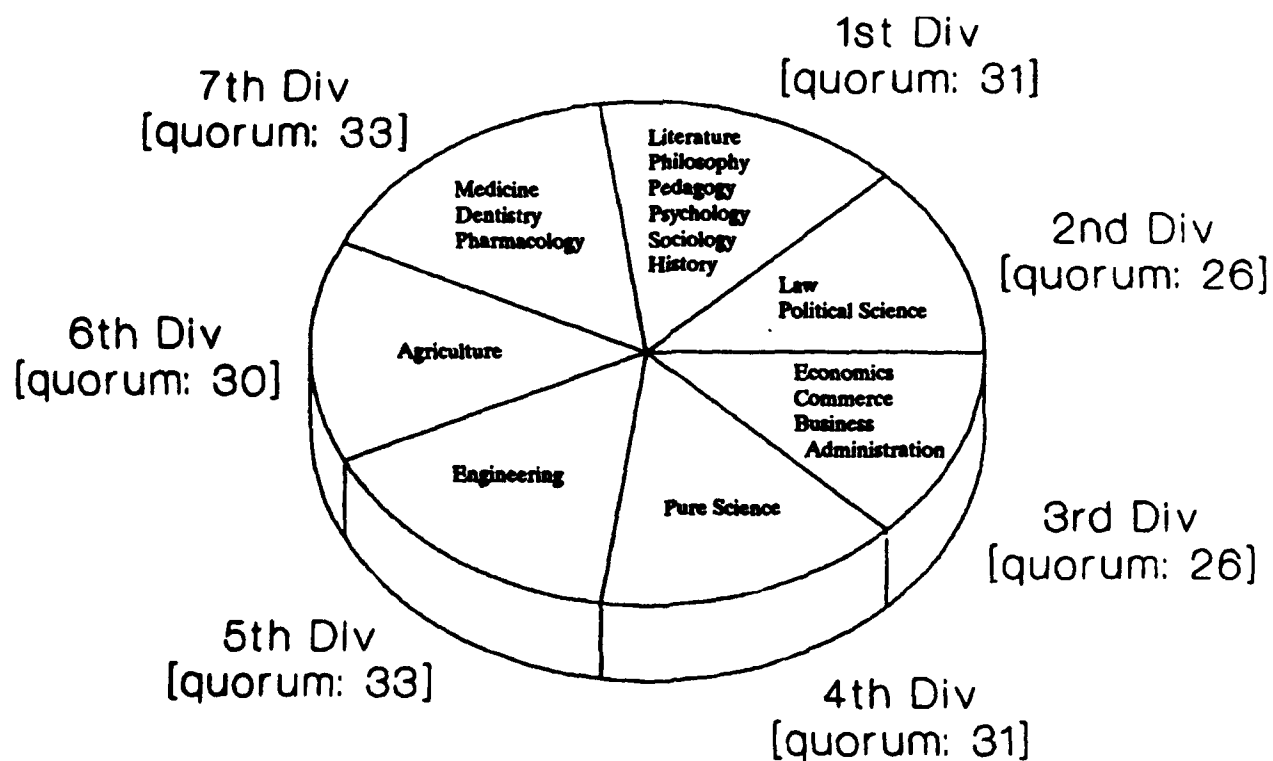


Figure 2. Structure of Science Council of Japan (cultural & social sciences and natural sciences).

**Table 1. 124 Disciplines in 71 Groups**

**1st Division (Literature):**

**Language and Literature**

**Philosophy**

Philosophy

Science of Religion

**Educational Science**

Educational Science

Physical Education and Sports Science

**Psychology**

Psychological Science

Behavioral Science

**Sociology**

Sociology

Social Welfare and Security

**Historical Sciences**

Historical Sciences

Archaeology

**Area Studies**

Oriental and Asian Studies

Cultural Anthropology and Ethnology

Human Geography

**2nd Division (Law):**

**Basic Sciences of Law**

Basic Science of Law

Comparative Law

**Public Law**

**International Law**

**Civil Law**

**Criminal Law and Criminology**

**Social Law**

**Political Science**

**3rd Division (Economics):**

**Economic Theory**

**Economic Policy**

**International Economics**

**Economic History**

**Public Finance Money and Banking**

**Commercial Science**

**Business Management**

**Accounting**

**Economic Statistics**

**4th Division (Natural Science):**

**Mathematics**

**Physics and Astronomy**

Physics

Astronomy

**Chemistry**

**Biological Sciences**

Zoological Science

Plant Science

Ecology and Environmental Biology

Cell Biology

Genetics

Molecular Biology

**Anthropology**

Anthropology and Ethnology

**Geological Sciences**

Geology

Mineralogy

Geosciences

**Geography**

**Geophysics**

Geodesy and Geophysics

**Science Education**

**Statistics**

**Information Sciences**

**Nuclear Science**

Radiation Sciences

**5th Division (Engineering):**

**Engineering Sciences**

**Applied Physics**

**Mechanical Engineering**

Thermal Engineering

**Electrical Engineering**

**Electronic Engineering**

Electronic & Communication Engineering

**Information Engineering**

**Civil Engineering**

Disaster Research

**Architecture**

Research for City and Area Planning

**Metallurgy**

**Applied Chemistry**

Material Research

(continued)



Table 1. Continued

**5th Division (Engineering) (continued):**

Natural Resource Engineering  
 Naval Architecture  
 Instrument and Control Engineering  
     Automatic Engineering  
 Chemical Engineering  
 Aeronautical and Space Engineering  
 Nuclear Engineering  
 Managerial Engineering

**6th Division (Agriculture):**

Agricultural Science  
     Agricultural Science  
     Plant Protection  
     Breeding  
 Agricultural Chemistry  
     Nutrition and Food Science  
     Science of Soil and Plant Nutrition  
     Agricultural Product and Fermentation  
 Science  
     Engineering Biotechnology  
 Forestry  
     Wood Science  
     Forestry  
     Forest Engineering  
 Fisheries Science  
 Agricultural Economics  
 Agricultural Engineering  
     Irrigation and Drainage  
     Agricultural Machinery  
     Environmental Engineering in Agriculture  
     Rural Planning  
 Animal Science  
 Veterinary Science  
 Sericultural Sciences  
     Inter-Agricultural Sciences  
     Conservation of Nature  
     Microbiology

**7th Division (Medicine):**

Biophysiological Sciences  
     Anatomy  
     Physiological Sciences  
     Brain Research  
     Biochemistry  
     Pharmacology  
 Pathological Sciences  
     Pathology  
     Reproduction and Developmental Anomalies  
     Medical Genetics  
     Aging  
     Infectious Diseases and Immunology  
 Internal Medicine  
     Cardiovascular Research  
     Endocrinology  
     Hematology  
     Metabolic Disorders  
     Digestive Diseases  
     Psychiatry  
     Radiology and Medical Electronics  
 Surgical Medicine  
     Digestive Surgery  
     Cardiovascular Surgery  
     Thoracic Diseases  
     Functional Recovery Medicine  
     Emergency Medicine and Anesthesiology  
 Social Medicine  
     Hygiene  
     Legal and Social Medicine  
     Preventive Medicine  
     Urban and Rural Medicine  
 Dentistry  
     Cariology and Periodontology  
     Occlusal Reconstruction  
     Oral Function  
 Pharmaceutical Sciences  
     Medical Pharmacy  
     Pharmaceutical Chemistry and Physics  
     Biopharmaceutical Sciences

1. Science in Japan, status and problems
2. Profile of research activities in science
3. Trend and phase
4. Present status of research activities in science
5. Level of Japanese science as compared with the international standard
6. Prospects and impediments of science in Japan

The JSC submitted the final report of 400 pages, titled "Trend of Science in Japan," to the 104th General Assembly in April 1988. The Table of Contents of this report is included as the Appendix to this article.

### **DYNAMIC CHANGE IN SCIENTIFIC RESEARCH**

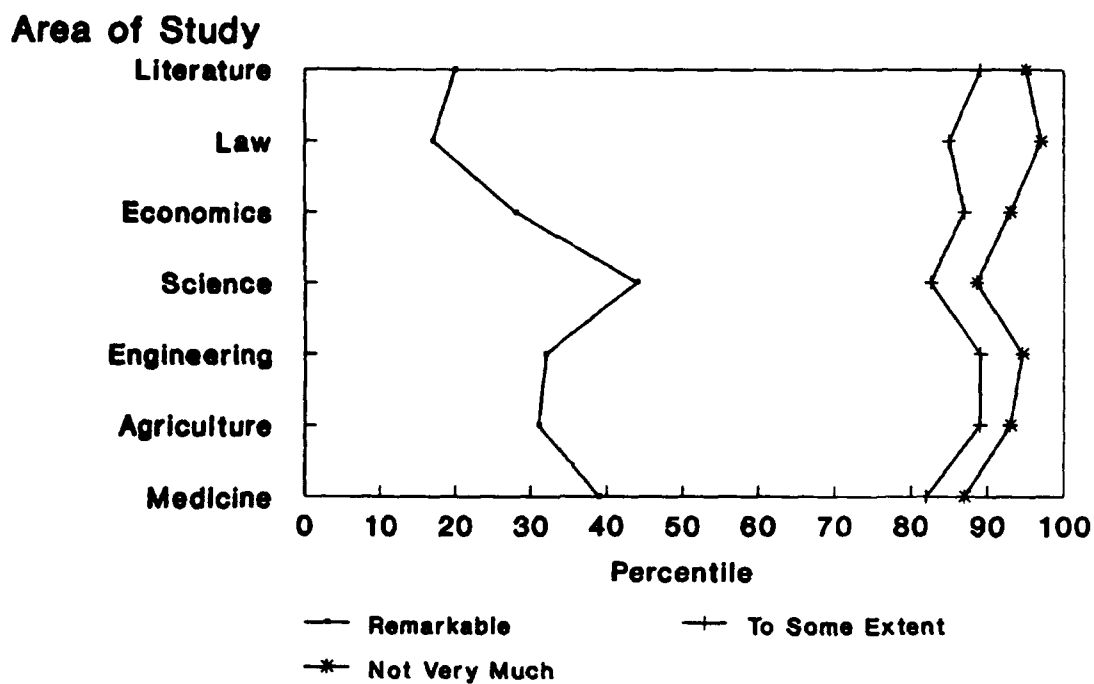
Considerable changes in theme, methodology, and instruments of scientific research have been observed in the past decade. Based on the responses of individual scientists as shown in Figure 3a, the most dynamic change is in natural science (44%), followed by medicine (39%), engineering (32%), agriculture (31%), economics (28%), literature (20%), and law (17%). However, a steady change is taking place even in law, where the introduction of computers has brought about an increase in quantitative and mathematical analysis.

The use of high-speed computers for observation, analysis and measurement instrumentation, and data analysis has

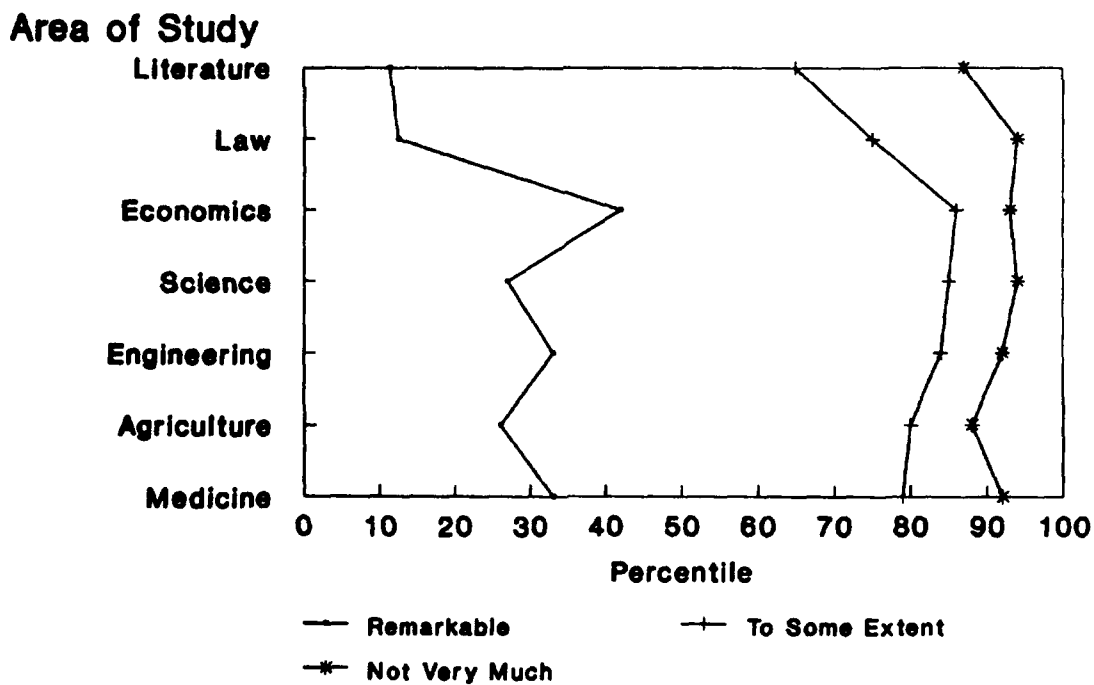
expanded the field of research from macroscopic space phenomena to microscopic life phenomena in the past decade. On the other hand, the gap and tension between two extremes, such as deepening of traditional science and the development of new fields, basic research versus applied science, and "big" science using huge equipment and "small" science by individual ideas, are widening.

### **THE LEVEL OF JAPANESE SCIENCE**

When the level of science in Japan is evaluated by individual scientists and societies in their own discipline, there is a very good feeling about the contributions based on an international standard. The response is shown in Figures 4a and 4b. However, when asked to evaluate the general level of science the evaluation of the overall field of science is a bit more pessimistic. This is a reflection of the concern by the Japanese that the early contributions that shaped science as we know it today were mainly from other countries. This, of course, is a contradiction to the responses by individuals and their societies about their view of themselves, which is a contemporary one. This is readily apparent when one compares the response data in Figure 5 with Figures 4a and 4b. It may also have something to do with the age of the respondents, their relative lack of appreciation of allied fields because of specialization, or that the nature of the question elicited such a response. It is acknowledged that this brief communication may not do justice to the extensive report and more detailed interpretations may result from further study.

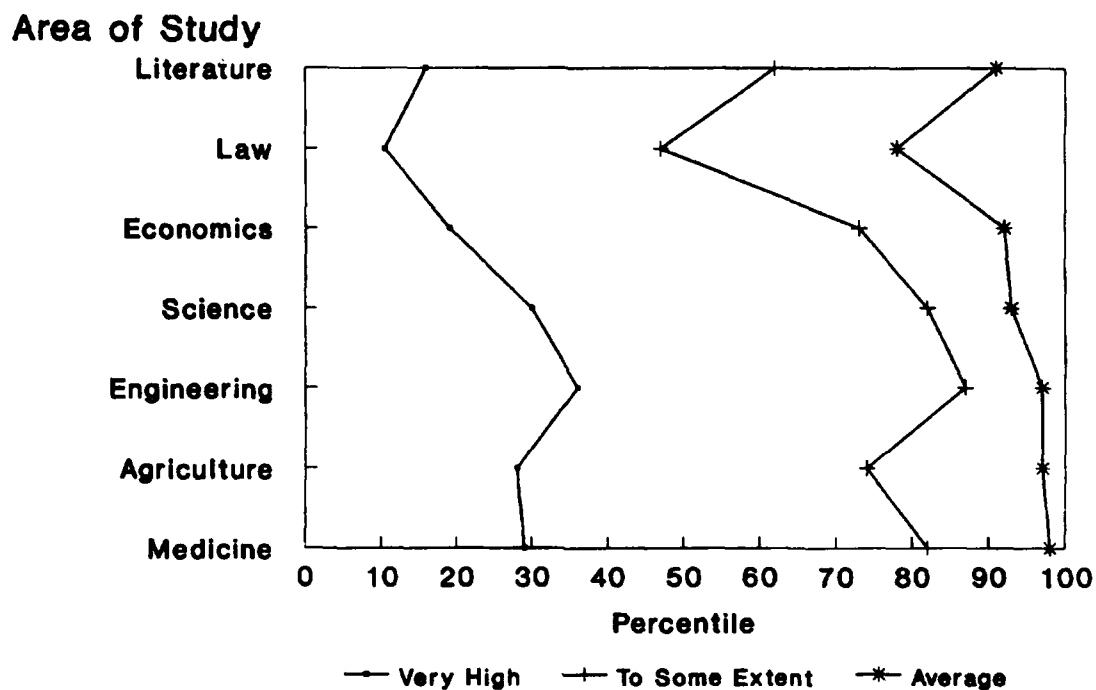


(a) Results for scientists.

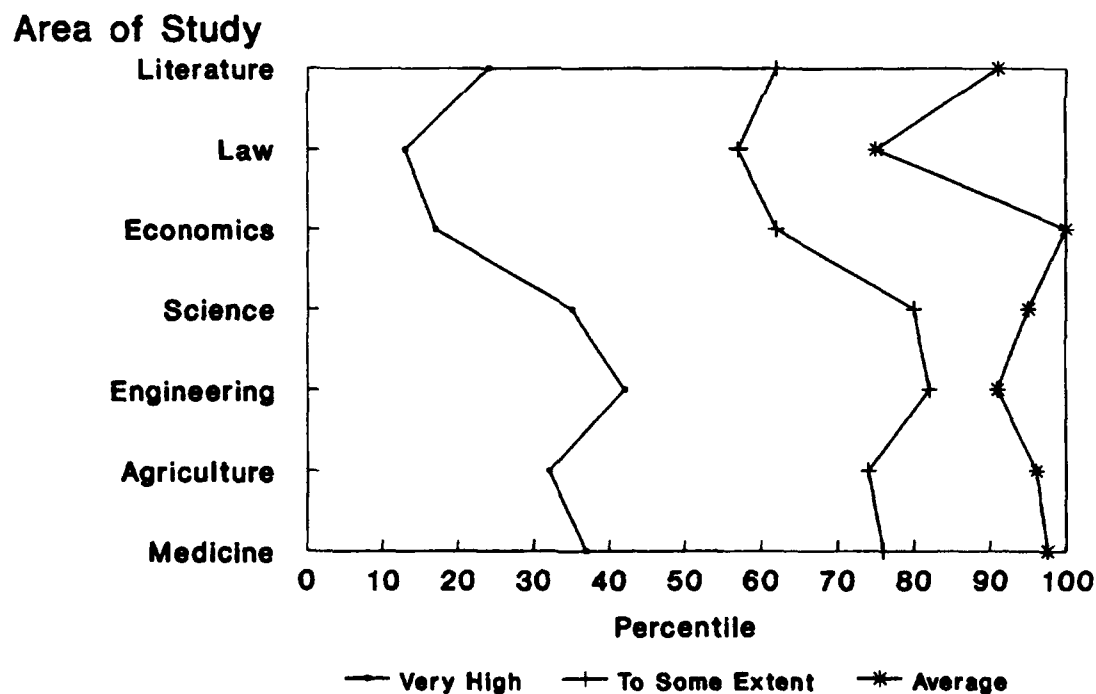


(b) Results for academic societies.

Figure 3. Dynamic change in scientific research.



(a) Results for scientists.



(b) Results for academic societies.

Figure 4. The level of Japanese science (particular field).

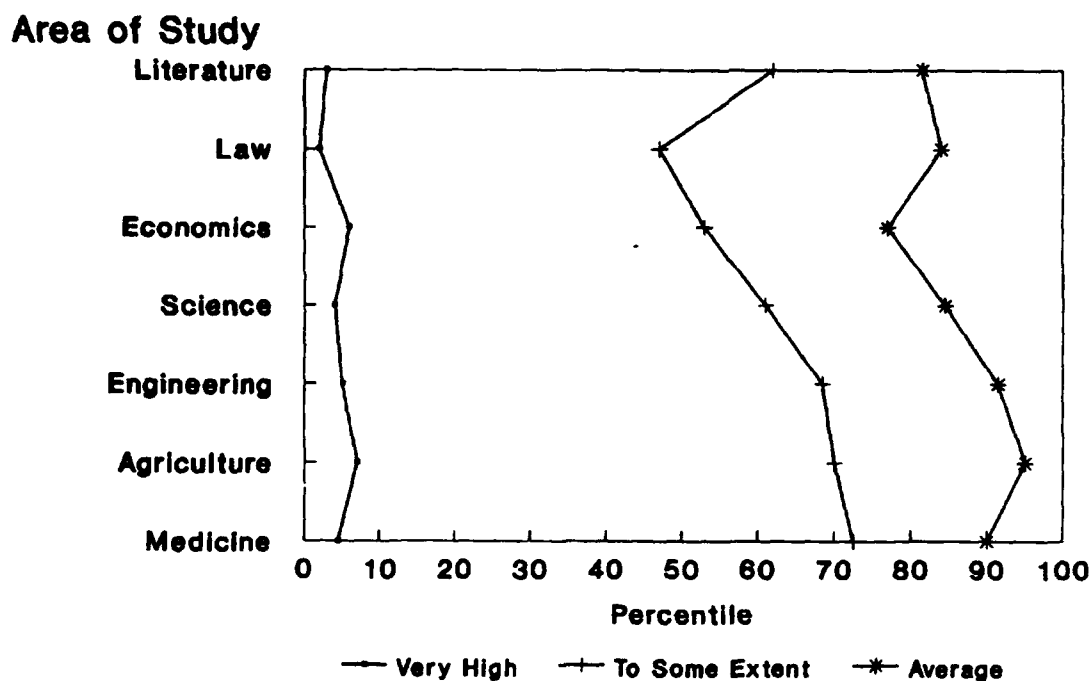


Figure 5. The level of Japanese science (general) (by academic societies).

## IMPEDIMENTS TO THE PROGRESS OF SCIENCE

Impediments to the progress of science that need to be solved are shortages of research funds (31%), methods of training scientists (28%), research system (23%), international exchange of researchers (13%), and data bases (17%) (see Figure 6).

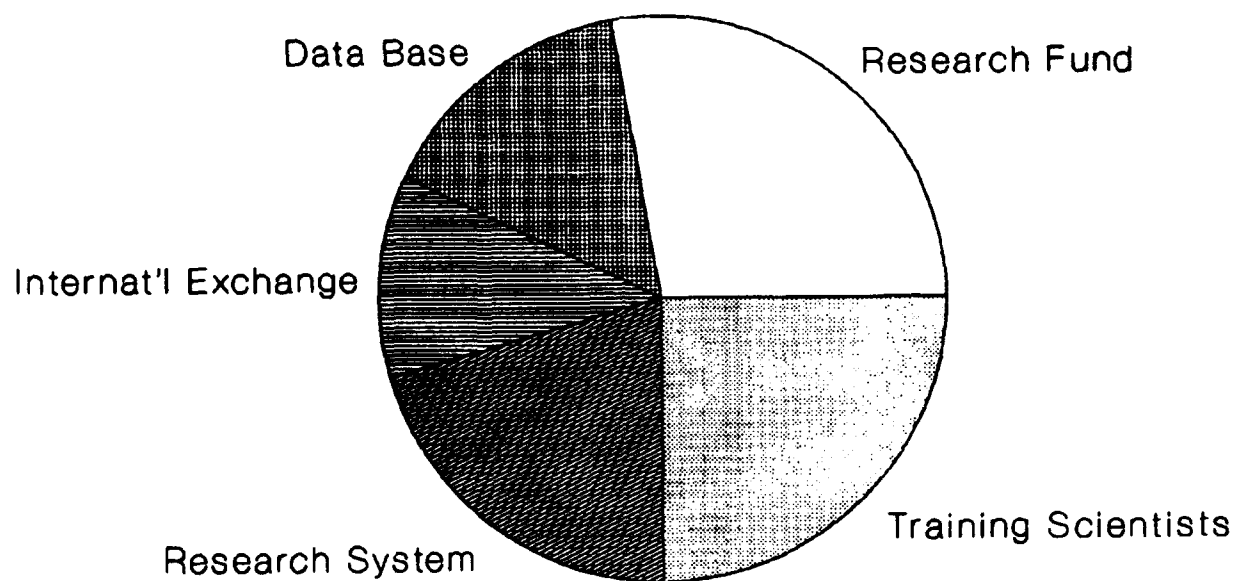
Although the total expenditure for research and development has increased in the past decade, most of the increase has been provided by private enterprises. The rate of increase in governmental funding is very small. This means that the level of basic research expenditure in the overall

R&D budget is very small. The Government should provide more funds to stimulate basic research.

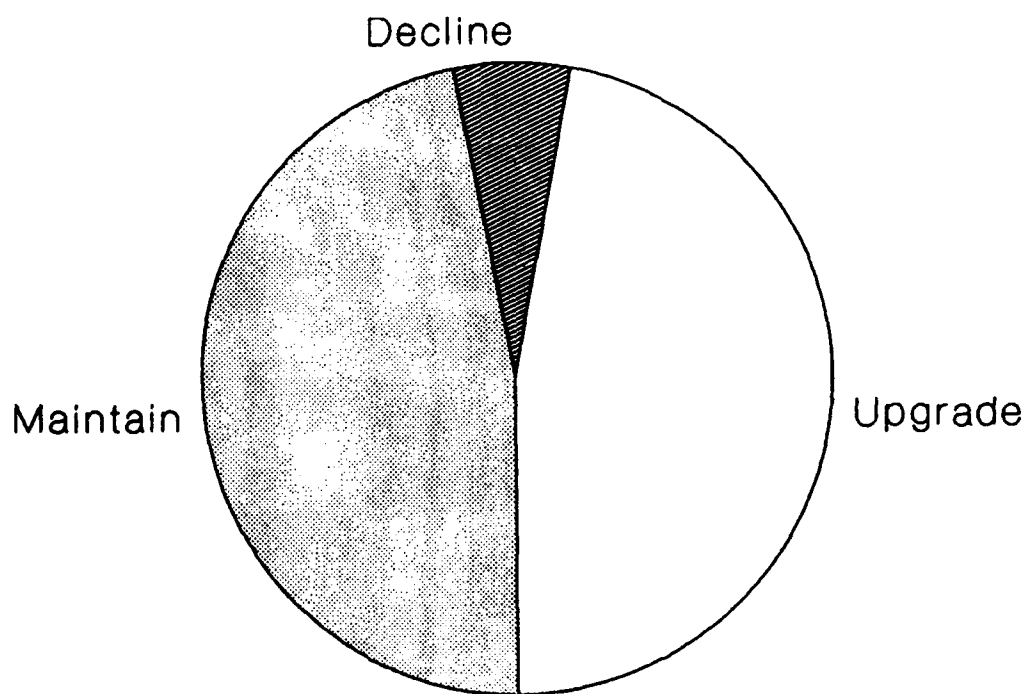
In the academic community, job mobility and evaluation of research achievement should be improved. In addition, young scientists should have more opportunities to study abroad.

## CONCLUSION

Scientists are generally optimistic for the future of Japanese science, as indicated in Figure 7. This issue is discussed in much greater detail in "Science in Japan," by the author (International Council of Scientific Unions Symposium, Beijing, China, 14 September 1988).



**Figure 6. Impediments to the progress of science.**



**Figure 7. Future of Japanese science.**

*Jiro Kondo received an undergraduate degree in mathematics from the Imperial University of Kyoto in 1940, a graduate degree from the Imperial University of Tokyo in 1945, and a doctor of engineering from the University of Tokyo in 1958. In 1958 he was promoted to professor of applied mathematics and gas dynamics in the Department of Aeronautics at the University of Tokyo. Prof. Kondo served as the dean of the Engineering School, University of Tokyo, from 1975 until his retirement in 1977, when he became Professor Emeritus. In 1977 Prof. Kondo joined the National Institute for Environmental Studies in Tsukuba Science City, first as deputy director and then, from 1980-85, as director. From 1985-88 he served as president of the 13th term of the Science Council of Japan, and recently he was*

*reelected as president for the 14th term (1988-91). Prof. Kondo is also an ex-official member of the Science and Technology Council of the Prime Minister's Office. He is the author of some 50 books and more than 150 papers on applied mathematics, theoretical aerodynamics, management sciences, systems engineering, and environmental science. His book, Managerial Science, was awarded the 1986 prize from the Japan Management Society. Prof. Kondo is an honorary member of the Japan Rocket Society, Japan Society for Aeronautical and Space Sciences, and the Japan Operations Research Society, of which he was president from 1984-86. In 1982 he was granted the Purple Ribbon Metal for his outstanding academic research in applied analysis and environmental research.*

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**List of Writers and Members of the Third Standing Committee**

# FIFTH INTERNATIONAL CONFERENCE ON MOLECULAR BEAM EPITAXY (MBE-V)

Kiyoshi Takahashi and Earl Callen

**A**t MBE-V in Sapporo there were talks on how to reduce diffusion and surface roughness through migration-enhanced epitaxy at lower substrate temperatures, the advantages of chemical beam epitaxy (CBE) and photon-assisted MBE and CBE, industrial process high electron mobility transistors (HEMTs) by MBE, strained layer Si/Ge superlattices, p-type doping of II-VI materials in MBE, electric field-induced localization and optical effects of electric fields, high mobility systems, and low-dimensional structures (quantum wires and dots).

## INTRODUCTION

The Fifth International Conference on Molecular Beam Epitaxy (MBE-V) was held at Hokkaido University, Sapporo, Japan, from 28 August to 1 September 1988, followed by a 1-day (2 September) First Workshop on CBE/MOMBE/GSMBE. Conference topics were Growth Kinetics; Si-Ge Heterostructures; Si, Silicides, and Oxides; GaAs on Si; Gas-Source/MOMBE and CBE; MBE for Production; II-VI Compounds; Modulation-Doped

Structures and Impurity Segregation; Optical Properties of Quantum Wells and Tunneling; Novel Low-Dimensional Structures, Growth on Vicinal Surfaces; Strained Layer Structures; High T<sub>c</sub> Superconductors; MOCVD; Band Discontinuity; MBE-Grown Devices; Novel Material Systems; and Novel Heterostructures.

## HISTORY

First some history and definitions.\* References 2, 3, and 4 list a few recent conference proceedings. Evaporated films of lead and tin chalcogenides were widely studied in the 1940s, "although superior epitaxy was not achieved until 1964 when Schoolar and Zemel (Ref 5) [at the Naval Ordnance Laboratory, White Oak, a.k.a. Naval Surface Weapons Center] clearly demonstrated the growth of epitaxial PbS films on NaCl using molecular beams generated from effusion cells. This work probably constitutes a precursor of the modern MBE technique" (Ref 2). Gunther (Ref 6) had already shown how to grow stoichiometric, although not epitaxial, films of the III-V compounds, and in 1968 Davey and Pankey (Ref 7) produced epitaxial films on

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\*Optoelectronics, MBE research, and ACRONYMs are growth fields. Consider the following. (a) The Japanese optoelectronics industry "did not exist in 1980, accounted for \$4.8 billion in sales in 1985, and is projected to amount to \$60 to \$70 billion in sales by the year 2000" (Ref 1). (b) At Sapporo 437 attendees heard 146 talks in 4 days of parallel sessions. This is a 25-percent attendance increase over the fourth (previous) conference in 1986. (c) The ACRONYM high point of the Sapporo meeting was the session on SLB GRIN-SCH-SQWs, PIN/HEMT-OEICs, SAGM-APDs, and other MISFETs.

clean monocrystalline GaAs substrates. Extensive investigations by Arthur (Ref 8) on the growth kinetics of Ga and As on GaAs laid the foundation for the production of high quality III-V films by molecular beam epitaxy (MBE). But an intriguing

idea that has stimulated interest in MBE from that day to this was the ingenious conception by Esaki and Tsu (Ref 9) in 1969 of superlattices--one-dimensional periodic structures of alternating, ultrathin layers

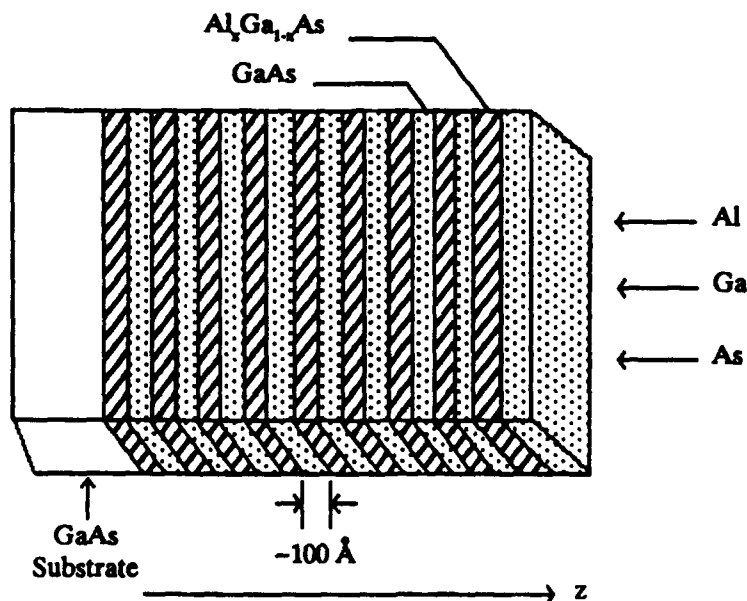


Figure 1. GaAs/ $\text{Al}_x\text{Ga}_{1-x}\text{As}$  superlattice. Epitaxial layers are deposited on a GaAs substrate. In an optoelectronic device there may be 3,000 such layers. Unlike the single quantum well devices, in the superlattice the  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  barrier (large bandgap) layers must be thin enough to allow tunneling.

In early molecular beam epitaxy the material, in elemental form, was evaporated from Knudsen cells, the beam entering a vacuum chamber and depositing on the substrate. In gas-source MBE (GSMBE), molecular gases replace some or all of the elemental solid sources (Ref 10). Silane ( $\text{SiH}_4$ ), arsine ( $\text{AsH}_3$ ), and

phosphine ( $\text{PH}_3$ ) are commonly used. In metalorganic molecular beam epitaxy (MOMBE) the gas sources include column III metal alkyls of triethyl or trimethyl structure, such as  $\text{Ga}(\text{C}_2\text{H}_5)_3$  (TEG) or  $\text{Al}(\text{CH}_3)_3$  (TMAI). Whatever the sources, in MBE beams of molecules traverse the vacuum chamber and decompose on the target

substrate. The pressure ( $\sim 10^{-4}$  Torr) within the reactor is sufficiently low that the mean free path between molecular collisions exceeds the distance between the source inlet and the substrate. High vacuum equipment is expensive and cumbersome, but MBE has the great advantage of allowing in-situ monitoring of the evaporation process by reflection high-energy electron diffraction (RHEED), Auger electron spectroscopy (AES), secondary ion mass spectrometry (SIMS), x-ray induced photoelectron spectroscopy (XPS=ESCA), and transmission electron microscopy (TEM). In the intrinsically very much faster chemical vapor deposition (CVD) process (Ref 4), in contrast, pressures exceed  $10^3$  Torr and may be atmospheric. The dense source vapor [in metalorganic CVD (MOCVD) the constituents can be the same as in MOMBE] is in contact with the hot substrate at a stationary "stagnant" boundary layer. At the growth surface the source molecules are pyrolyzed and the column III and column V elements react to deposit the growing epitaxial III-V layer. A recent variant pioneered by Tsang (Ref 11) is chemical beam epitaxy (CBE). Here the pressure in the reactor is reduced to below  $10^{-4}$  Torr so that the trajectories are kinetic and "line of sight," as in MBE. All sources are gases, both of the group III and group V elements. The group V hydride source gases such as arsine and phosphine are decomposed into molecular  $As_2$  and  $P_2$  at the source inlet in a high temperature cracker within the reactor and beamed at the substrate. At a separate port the group III gases, perhaps TEG or TMIn, are introduced, beamed at the substrate, and pyrolyzed on the surface.

## QUANTUM WELLS, NEGATIVE RESISTANCE, SUPERLATTICES, NONLINEAR OPTICS

### Quantum Wells

A semiconductor is characterized by a valence band and a conduction band separated by an energy gap,  $E_g$ , in the allowed states. When an electron drops from the conduction band into an empty state in the valence band (electron-hole recombination), energy is lost by the pair. This energy can be transferred to the lattice, ultimately appearing as heat, radiated as light, lost in some other way, or some combination of the above. In silicon, optical emission is weak because emission of light requires emission or absorption of a phonon. In "direct gap" III-V compounds such as GaAs radiative recombination is more easily accomplished. Most of the recombination energy is radiated as light, which is therefore of energy and frequency  $E_g \approx h\nu$ . The III-Vs are a natural for solid state lasers. Because of this efficient conversion and because of their extraordinarily large electron mobilities, making for very fast devices, the III-Vs are the materials of choice for optoelectronics.

To understand tuning of the light frequency by quantum wells we must know something about the energy level diagram. The reader may recall that in a one-dimensional square well of width  $L$  and with infinitely high potential walls, the allowed energies of a particle of effective mass  $m$  are quantized and depend on the quantum number  $n$  as

$$E_n = \frac{\pi^2 \hbar^2 n^2}{2 m L^2} \quad (1)$$

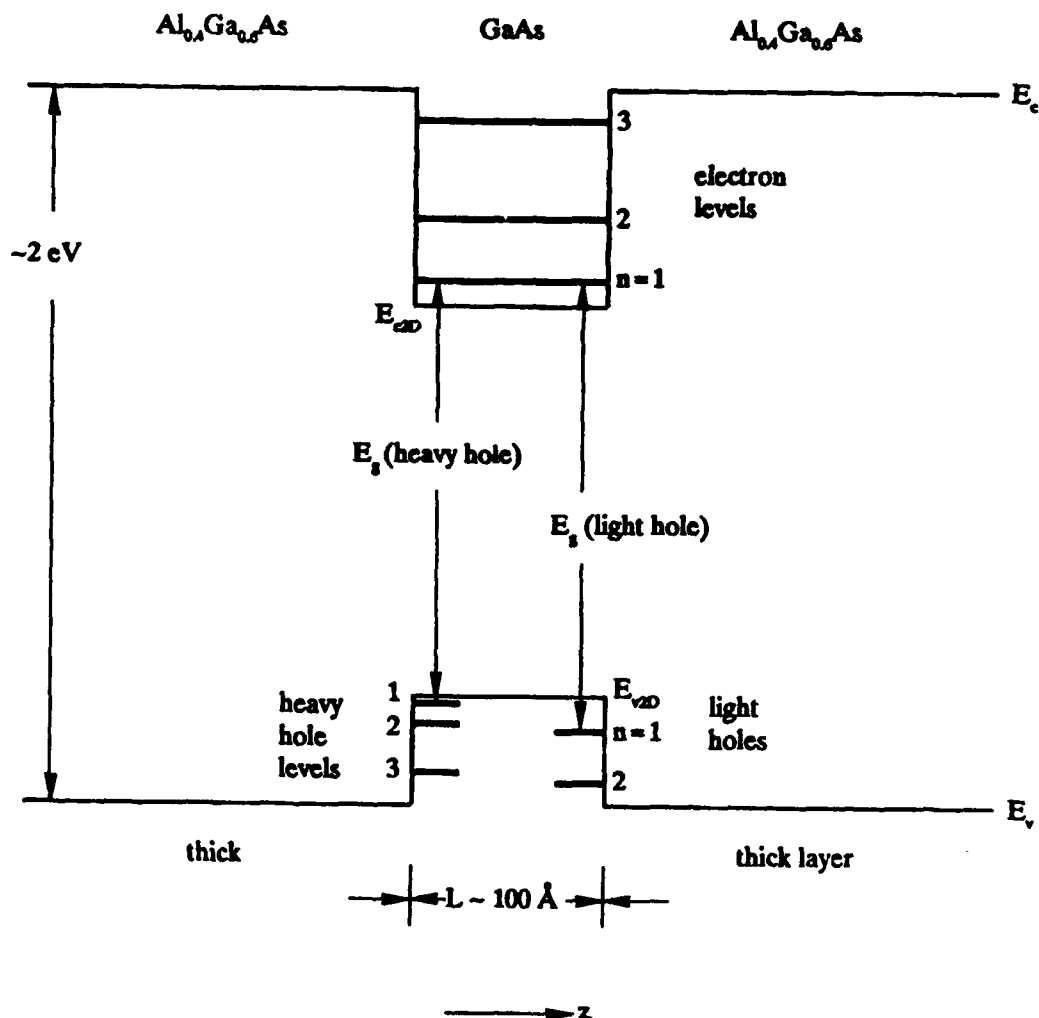


Figure 2. The single quantum well (SQW). Between two thick barrier layers of larger bandgap ( $\sim 2$  eV)  $\text{Al}_{0.4}\text{Ga}_{0.6}\text{As}$  is a thin (100 to 150 Å) layer of GaAs. Conduction and valence band edges of the two materials are depicted with an arbitrary band offset and with the gap of the two-dimensional (2D) layer of GaAs reduced from its bulk value of about 1.5 eV. There are electron and hole states in the GaAs layer, quantized longitudinally as in Equation 1, but with the transverse energy of Bloch waves in the layer. Because of the light and heavy hole bands of bulk GaAs, there are two sets of hole states in the channel. The electron-hole recombination energies, the optically radiated energies, or the "effective gap" of the channel is the difference in energies between the electron and (two sets of) hole levels in the layer. We label these  $E_s$ (heavy hole) and  $E_s$ (light hole) for clarity.

On the other hand, in a crystal, because of the periodic potential, the allowed states are Bloch waves and the energies are grouped into quasi-continuous bands such as the valence band and conduction band,

with upper and lower band edges  $E_v$  and  $E_c$  (see Figure 2). What happens in a conducting layer, in which electrons are confined to a narrow, two-dimensional trench, free to wander in the x-y plane but contained along

z within a region of width L comparable to or smaller than their deBroglie wavelength? Imagine such a planar, two-dimensional layered structure. On a substrate we have a thick barrier layer of  $\text{Al}_x\text{Ga}_{1-x}\text{As}$ . On this has been deposited perhaps 100 to 150 Å of GaAs, the well, and then another few hundred Angstroms of  $\text{Al}_x\text{Ga}_{1-x}\text{As}$ , with  $x = 0.4$  or so. This is the quantumwell (QW), or single quantumwell (SQW), whose energy band structure is illustrated in Figure 2. The Al ternary compound is convenient because it has a significantly larger energy gap than does GaAs, and the two lattice constants match to better than 0.05 percent. For some pairs of III-Vs, especially GaAs with  $\text{Al}_x\text{Ga}_{1-x}\text{As}$ , and InP with  $\text{Ga}_x\text{In}_{1-x}\text{P}$ , with the correct ratio of x to y, energy gap and refractive

index can be considerably modified with almost no change in lattice constant. Of course one can lay down thin barrier layers that permit electron tunneling between wells, and connect these in multiple-layered superlattices, as in Figure 1, and we shall soon progress to the properties of these more complex structures. But for now let us consider the SQW, with barrier layers so thick as to preclude tunneling, and let us suppose the bandgap of the  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  to be very large. In fact, for the moment, let us treat it as infinite. Even so, we must know how the band edges of the two materials line up--there is some "band offset" to be measured and calculated. These are known for the GaAs/(Al,Ga)As system. But let us beg that question. What are the allowed energies? In Box 1 we show how to calculate them.

### Box 1. The Thin Two-Dimensional Periodic Potential

The time-independent Schroedinger equation for a particle of effective mass m in potential V is:

$$\frac{-\hbar^2}{2m} \nabla^2 \psi + V(x,y,z) \psi = E \psi \quad (\text{B1-1})$$

Since the potential separates into the periodic transverse part  $V(x,y)$  along the GaAs layer plus the longitudinal potential  $V(z)$  perpendicular to the layers, we can write the wavefunction as a product  $\psi(x,y,z) = B(x,y)W(z)$ . The energy E we decompose into the sum

$$E = E_{x,y} + E_z \quad (\text{B1-2})$$

The Schroedinger equation then separates as

$$\frac{-\hbar^2}{2m} \frac{(\nabla_x^2 + \nabla_y^2) B(x,y)}{B(x,y)} + V(x,y) = E_{x,y} = \frac{-\hbar^2}{2m} \frac{\nabla_z^2 W(z)}{W(z)} - V(z) + E_z$$

. . . . . (B1-3)  
(continued)

## Box 1. Continued

The transverse equation, transformed to momentum space, has Bloch wave solutions  $B(k_x, k_y)$  representing electrons and holes traveling along transversely in the GaAs. Their energies are bunched into bands, with a gap  $E_{gd}$  between the conduction and valence band edges. The solution of the longitudinal equation is complicated by the periodicity of the potential across the (perhaps) 30 atoms of GaAs, but this is far from the infinite crystal of which the solutions are Bloch waves. There will be surface states (which we ignore). For low energy solutions of long wavelength the boundary conditions override the periodicity. The low-lying solutions are approximately those of the one-dimensional square well, as in Equation 1. This is known as the "envelope function" approximation. Since electrons and holes have different effective masses (this comes from the transverse Bloch solutions; there are in fact two hole masses--light and heavy holes), they have different energies. Total energies are the sums of transverse and longitudinal energies. States in the channel are shifted away from the band edges in the channel, and "effective bandgaps" are the recombination energies of electrons with light and heavy holes. This is illustrated in Figure 2. Since the longitudinal energy levels depend upon the width of the well, changing the thickness of the GaAs layer alters the electron-hole recombination energy and the energy of the radiated photon.

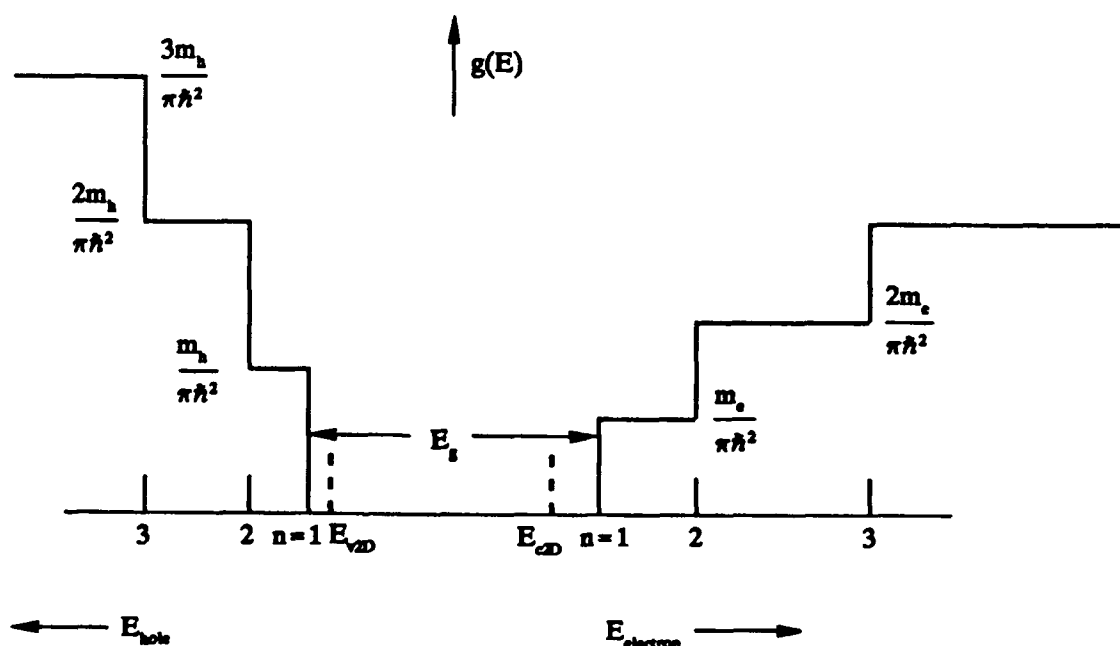


Figure 3. Density of states of the thin quantum well. Electron energies increase to the right, hole energies to the left. Steps occur at the discrete energies of the well but are differently spaced because of the different masses,  $m_e$  and  $m_h$ . Only one hole mass is illustrated. Electron and hole state densities increase at each level in steps of  $m_e/\pi\hbar^2$ . Levels increase in energy as  $n^2$ .



## Tunneling, Resonant Tunneling, and Negative Resistance

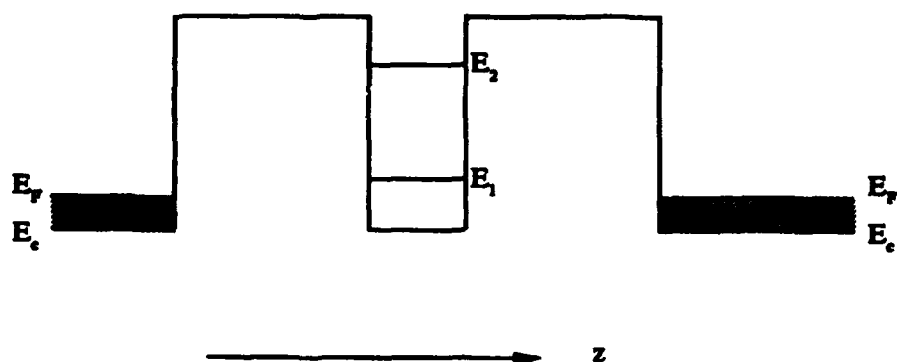
The reader will recall that, unlike in a classical system, in quantum mechanics the probability is nonzero for a particle to be in regions in which its total energy is less than the potential energy. Like the Poynting vector of electromagnetic waves, particle waves penetrate barriers. For example, if the potential is constant in the barrier, the electron wavefunction, the solution of the Schroedinger equation (Equation B1-1), falls off exponentially from the surface (depending upon boundary conditions; it can also increase). And if the potential is not too high and the barrier is not too thick, the electron can in a reasonable time penetrate through to a low potential, propagating region on the other side. That is quantum mechanical tunneling.

In his Nobel lecture, Esaki (Ref 12) described a negative resistance, resonant tunneling, double barrier device (also see References 13 and 14). (Esaki's tunnel diode research preceded his introduction of superlattices.) On a substrate of degenerate n-type GaAs (with the Fermi level in the conduction band) he deposited a thin barrier layer of less than 100 Å of AlAs or of  $\text{Ga}_{0.5}\text{Al}_{0.5}\text{As}$ . On top of this he laid down the 40- to 50-Å GaAs quantum well layer, then another thin barrier layer, and finally a thick layer of degenerate n-type GaAs. This is the double barrier quantum well (DBQW). Were it referred to instead as the tunneling quantum well it would be better distinguished from the SQW. The DBQW is illustrated in Figure 4a, with two electron levels in the well. Electrodes are now connected, a voltage is applied between the substrate and the upper surface layer of

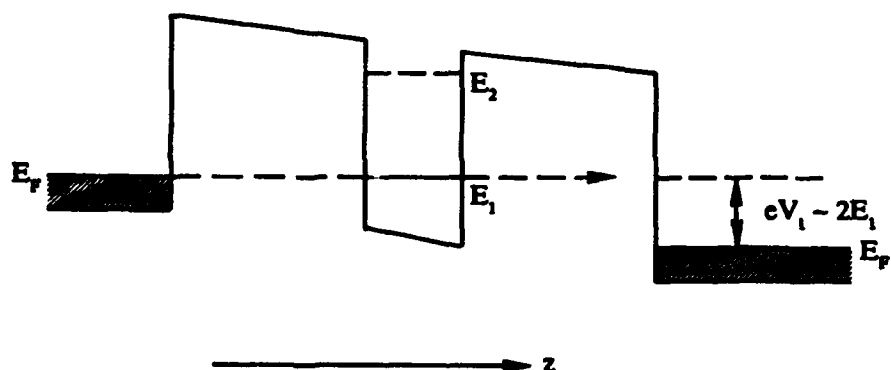
GaAs, and the current/voltage characteristic of the device is recorded. Conductance is "at resonance"--it has a peak--when the applied voltage is such as to shift a level in the well into coincidence with the Fermi level of the electron source. The current decreases as the applied voltage further increases due to a decrease in tunneling probability. This is the source of the "negative resistance." This is illustrated in Figure 4b. The current and the conductance ( $dI/dV$ ) are shown in Figure 5. With the same tunneling probabilities on both sides the device would be symmetric--the I/V curve would go into minus itself and the conductance curve into itself on reflection through the vertical, zero-applied-voltage axis. They do not in this example (Ref 12), but one can see resonant transmission negative peaks in the conductance. With increasing voltage the well energy levels progressively pass through the Fermi energy of the degenerate semiconductor source. The current rises as a well level shifts down into resonance, it peaks, and then it falls as the well level drops below the Fermi level. This is superposed on the generally rising I/V curve of Figure 5.

## Superlattices

In Figure 1 we showed a superlattice. This can be formed either compositionally, by laying down alternate, discrete, homogeneous layers, as in Figure 1, or by spatially oscillatory doping of a semiconductor, either continuously or in "delta doping" spurts. Superlattices created by doping are called "doping superlattices" or "NIPI superlattices." The band structures of compositional and NIPI superlattices are depicted in Figure 6.



(a) Zero-applied electric field.



(b) Resonant tunneling. At applied voltages such that a level in the well is shifted into coincidence with the Fermi level of an electron source, the conductance ( $dI/dV$ ) has a sharp negative maximum. Since the voltage drop is across both barriers, the resonance condition is that  $eV_1 \sim 2E_1$ . With a p-type source the same scheme would occur at the hole levels.

Figure 4. The double barrier quantum well (DBQW).

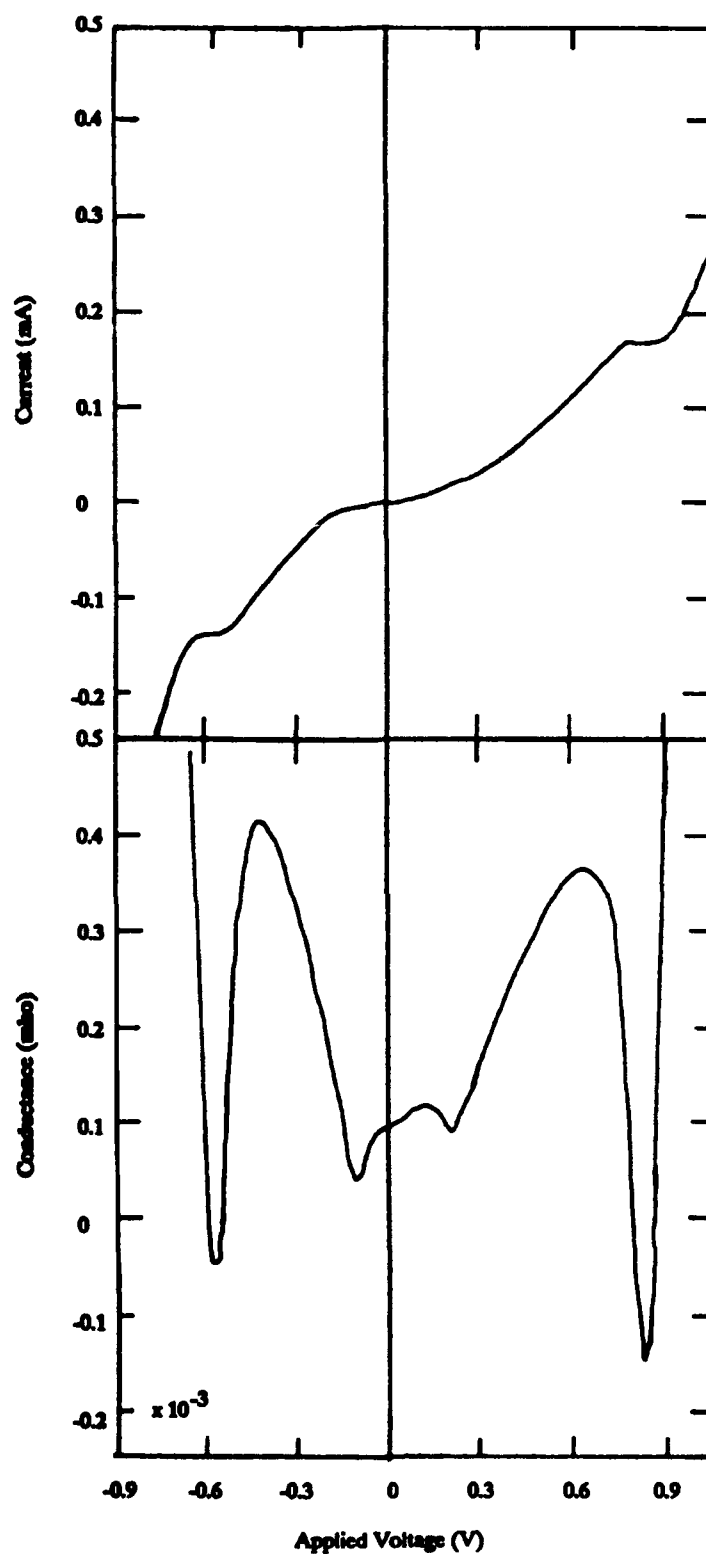
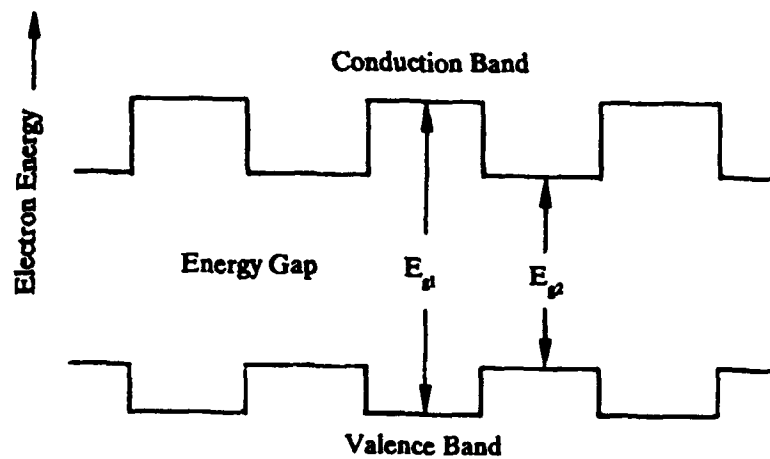
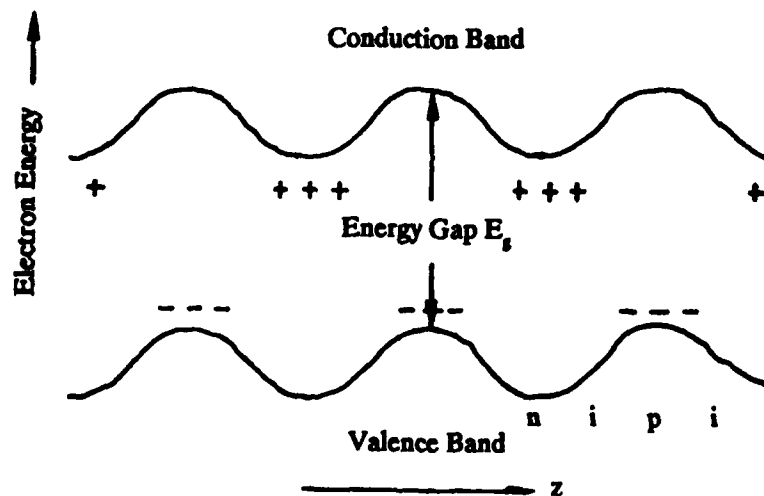


Figure 5. Negative differential resistance of the double barrier tunnel junction (or DBQW). The upper curve shows the current  $I$  versus voltage. The lower curve shows conductance  $dI/dV$  versus voltage.



- (a) Compositional superlattice. Homogeneous layers of different materials are alternately deposited, with fixed (and usually different) thicknesses for each material, so as to make a periodic structure. Note that the band offset need not be half the difference in bandgaps; the bumps at the valence band edge are not equal to the bumps at the conduction band edge.



- (b) NIPI superlattice. Ionized donors and acceptors contribute electrons and holes. The band edges conform to the potential, which satisfies Poisson's equation.

Figure 6. Periodic band structures of superlattices.

When an electron's deBroglie wavelength equals the lattice constant or any integral multiple thereof, the electron is Bragg reflected, just as are x rays in x-ray diffraction, and cannot propagate. This is the cause of the gaps in the energy spectrum. They occur over the surface of the Brillouin zone. What happens if we make many alternate  $\text{Al}_{1-x}\text{Ga}_x\text{As}$  and GaAs layers? Though the layers are thin, they are thick compared with the lattice constant; the period of this "superlattice" may be about 100 Å. In this structure the high wave-number (short distance) "carrier wave" of the atomic periodicity is modulated by the small  $k$  superlattice component. This

breaks up the Brillouin zone into mini-zones. Minibands replace the narrow levels depicted in Figures 2 and 3. In the superlattice analog (not shown) of Figure 2 the narrow well levels are broadened into subbands. Figure 7 shows the superlattice analog of Figure 3, the densities of states for the conduction and valence bands of the superlattice, again with only one kind of hole shown.

The existence of minibands implies novel electronic response. Suppose an electron of effective mass  $m$  is subjected to a longitudinal electric field  $E$ . From Newton's law,

$$F = -eE = m\dot{v} = \hbar\dot{k} \quad (2)$$

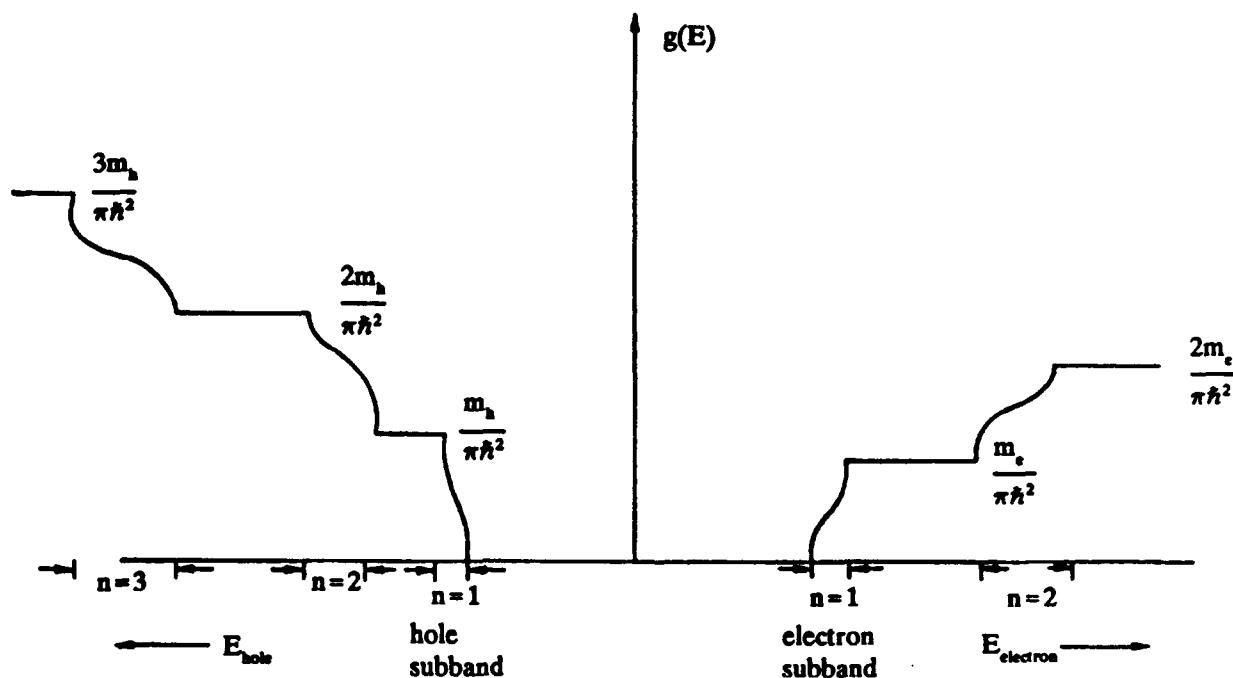


Figure 7. Density of states versus energy for the superlattice. Rises in the density of states occur over the ranges of energy of the minibands. These broaden at higher energies. The superlattice equivalent of Figure 2, allowed energies in the wells, is obtained by extending Figure 2 periodically and broadening the sharp levels in the wells into subbands.

Thus if there is no scattering the state occupied by the electron moves at constant rate through momentum space. As the electron gains energy from the electric field its energy approaches a forbidden gap between subbands and its wavenumber approaches a superlattice Brillouin zone boundary. The electron approaches Bragg reflection and it slows down (in real space). Positive force causes negative acceleration--the effective mass is negative. The velocity (in real space) is

$$v = (1/\hbar) dE/dk \quad (3)$$

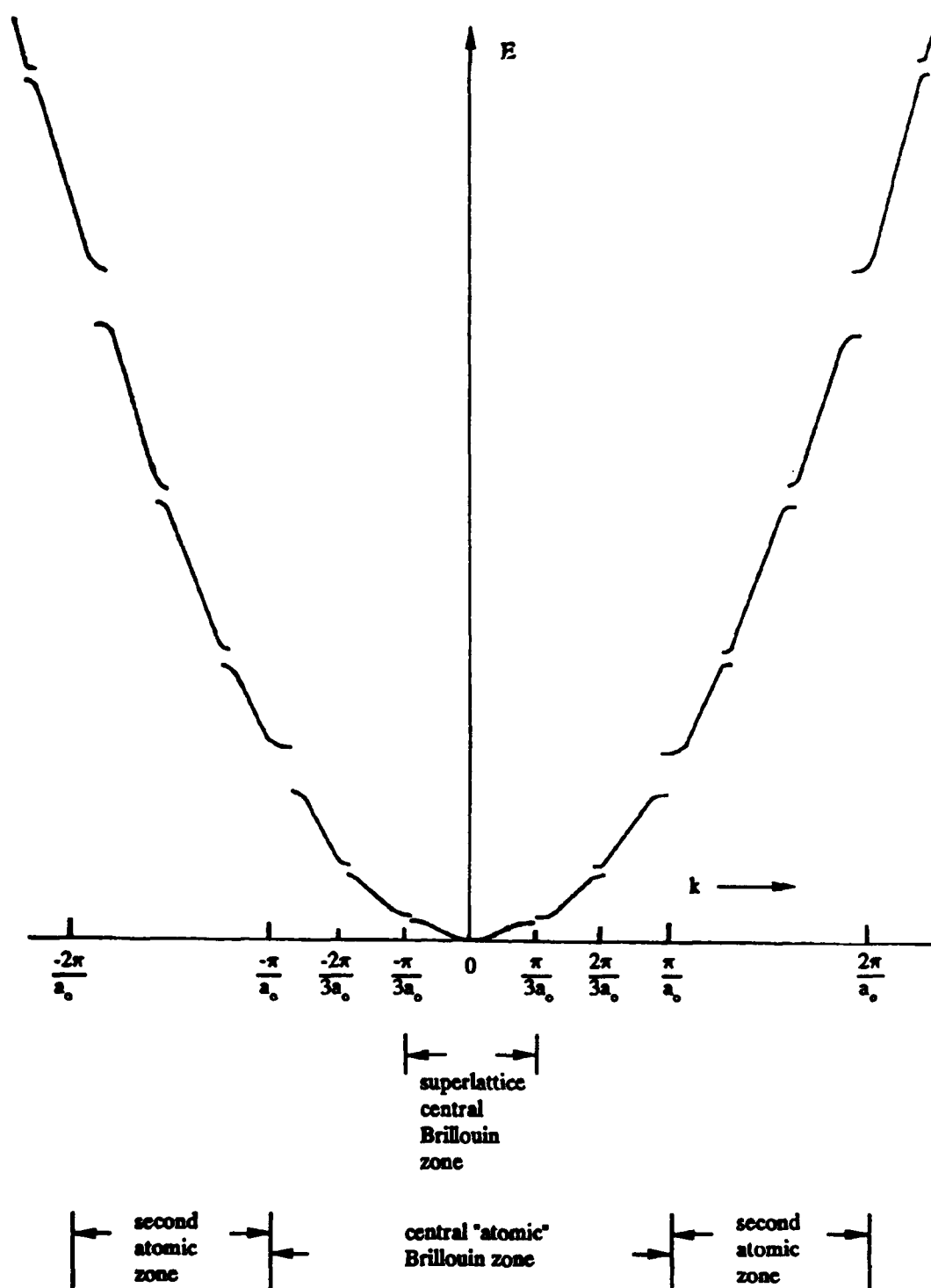
and this is zero at the zone boundary, where the slope is zero. Deceleration of the electron on approaching Bragg scattering manifests itself as negative conductance in the I/V characteristic of the superlattice.

Another useful way to envision this is by means of the dispersion curve  $E(k)$ , the way the energy of the electron depends upon its wavenumber. For the moment let us forget about Bloch waves, holes and electrons, and the periodic potential. Consider a free particle of mass  $m$ . Its kinetic (and total) energy is

$$E = \frac{\hbar^2 k^2}{2m} \quad (4)$$

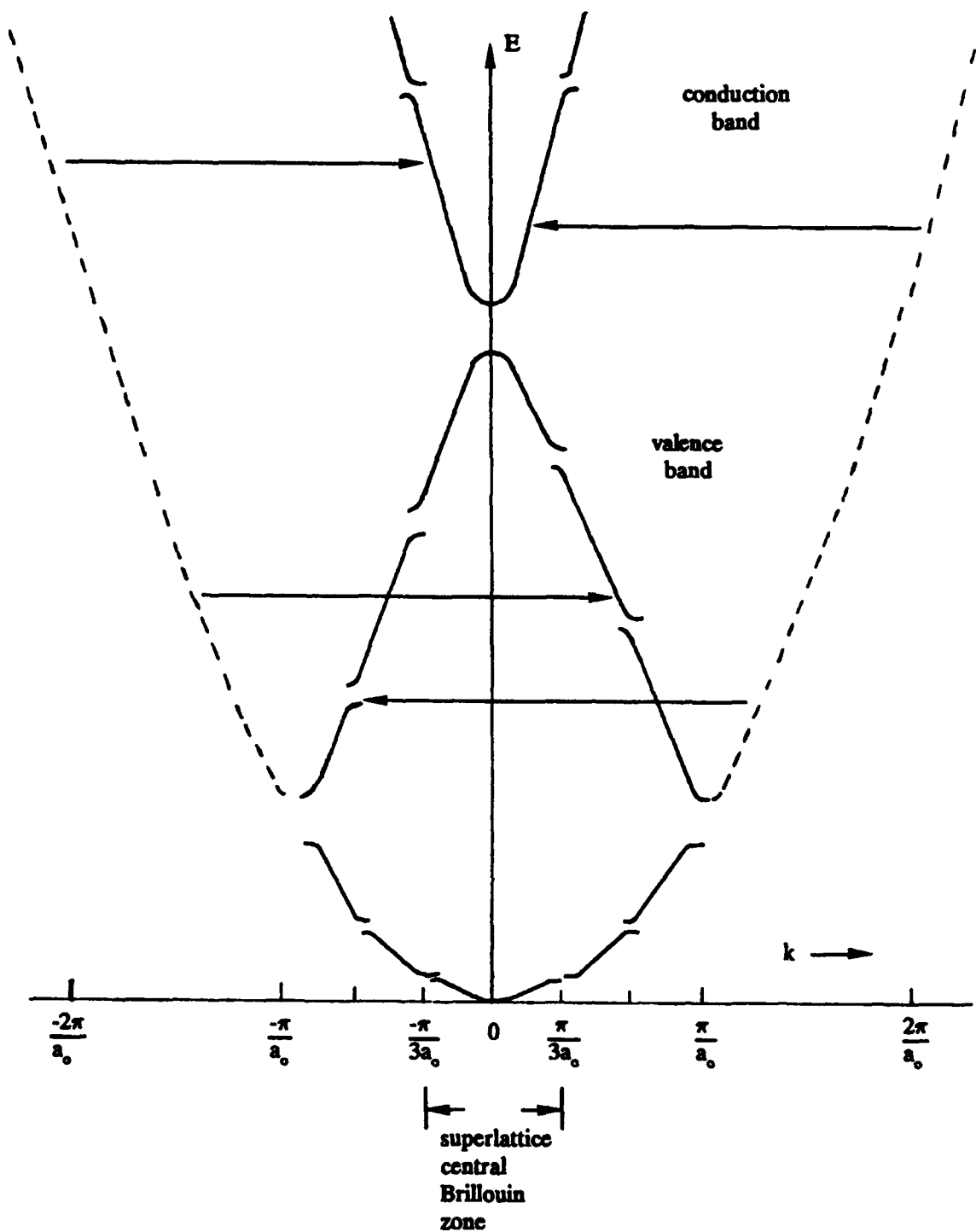
This parabolic dependence is shown by the dashed curve in Figure 8a. Now suppose the electron is in a small, perturbative superlattice periodic potential of period  $P$ , the superlattice repeat distance in real space, and for simplicity let us imagine this to be some multiple,  $P = Na_0$ , of the atomic periodic potential  $a_0$ . The first Brillouin zone of the atomic potential ranges from  $-\pi/a_0$  to

$\pi/a_0$ . At these zone boundaries (and all integral multiples) the Bragg condition is satisfied. There are gaps in the allowed energy and the derivative  $dE/dk$  is zero. The electron velocity in real space is zero as in Equation 3 above. This is shown by the solid curve in Figure 8a. But there is also the larger period of the superlattice and its smaller Brillouin zone boundaries at  $-\pi/Na_0$  and  $\pi/Na_0$  and all integral multiples. These also cause Bragg reflections, create gaps at the minizone boundaries, and force the normal derivative of the dispersion curve to be zero and the normal component of the electron velocity to be zero at the minizone boundaries and at these energies. This is also shown in Figure 8a, in the "free electron correspondence." Had we started not from free electron energies but from localized atomic energies and wavefunctions we would have been led to a single central Brillouin zone, and in it a series of dispersion curves at higher energies, one for each atomic energy level and wavefunction. We can get to this "atomic correspondence" by shifting the bands of the extended zone back into the central zone. Which zone? In Figure 8b we shift plus and minus by integral multiples of lattice vectors of the atomic (large) reciprocal lattice,  $2\pi/a_0$ , corresponding to the periodicity  $a_0$ . In Figure 8c we represent the perturbed dispersion curve in the central zone of the superlattice. To obtain the "superlattice correspondence" we shift by integral multiples ( $\pm$ ) of the superlattice reciprocal lattice vector  $2\pi/Na_0$ . As we shall soon see, the many gaps between minibands caused by Bragg scattering at superlattice zone boundaries, the negative mass and zero velocity near these momenta, have important physical and device implications.



(a) Free electron correspondence. There are gaps at all minizone boundaries, and atomic Brillouin zone boundaries, but  $E$  is drawn as a single-valued function of crystal momentum  $k$ , with  $k$  unbounded.

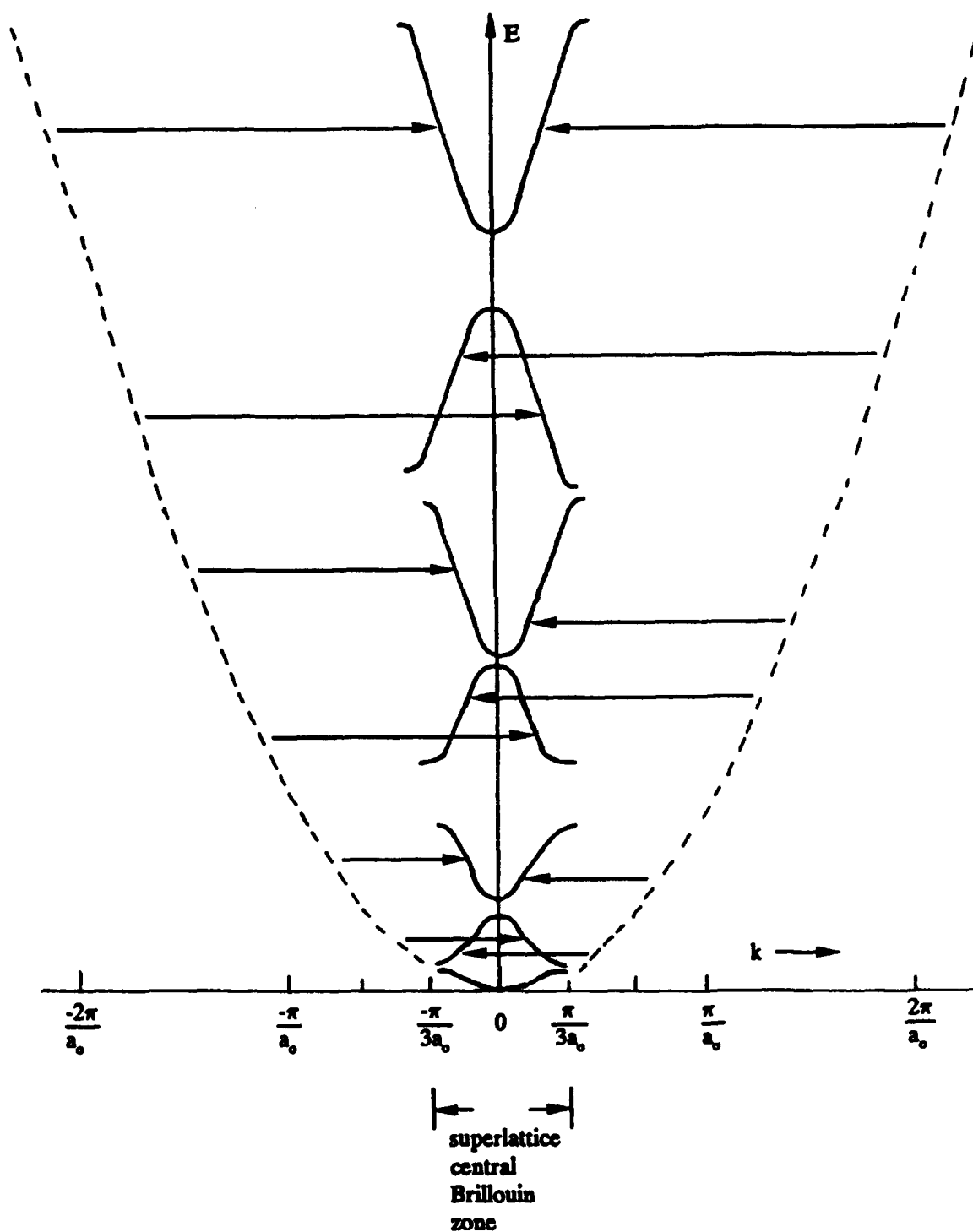
Figure 8. One-dimensional superlattice energy dispersion curves. For simplicity we illustrate the superlattice period as an integral multiple ( $N=3$ ) of the atomic period. In reality, since superlattices have two kinds of layers of different thickness, the arrangement of gaps and boundaries is a bit more complex.



- (b) Atomic correspondence. Outer ranges of the dispersion curve are shifted into the central zone by translation through integral multiples of the atomic reciprocal lattice vector  $2\pi/a_0$ . Only the lowest two "atomic" bands are portrayed. Had higher bands been drawn, gaps would also occur at the center of the zone, for example, between a valence and a conduction band.

Figure 8. Continued.





- (c) Superlattice correspondence. Branches of the dispersion curve are shifted into the central zone of the reciprocal lattice of the superlattice, corresponding to the superlattice periodicity  $Na_0$ . The superlattice reciprocal lattice vector is  $2\pi/Na_0$ . There are gaps between subbands and between bands from different atomic states. The one-dimensional superlattice misses the shifts of transverse subbands away from the 2D band edges.

Figure 8. Continued.

## Mean Free Path

Electron mean free path, of course, compares far more favorably with atomic lattice spacing than with superlattice period. But there is more to the physics. For the electron to respond with Bloch oscillations or even just with negative resistance to the periodic distance  $P$  (which is  $a_0$  in the usual crystal, and additionally  $Na_0$  in the superlattice), it must be unscattered for a time  $T$  long enough for its momentum to sweep through the Brillouin zone and be Bragg reflected. Since the reciprocal lattice vector is  $2\pi/P$ , the longer the periodic region in real space the shorter the zone in reciprocal space and (Equation 2) the shorter the time  $T$ :

$$T = \frac{h}{e E P} \quad (5)$$

In the degenerate case we can write this in terms of a mean free path. The mean free time equals  $\ell/v_F$ , with  $\ell$  the mean free path and  $v_F$  the Fermi velocity. The condition that the mean free time between collisions exceed the time between Bragg reflections then becomes

$$\ell > \frac{h v_F}{e E P} \quad (6)$$

This is far easier to satisfy in the superlattice, with its long period ( $\sim 20 a_0$ ), than in an ordinary crystal. It is also more easily met in clean materials with low Fermi velocity and at low temperature. Esaki (Ref 12) and coworkers (Ref 15) and others (Ref 16) have analyzed the scattering issue extensively. There is as yet no firm observation of Bloch oscillations in a semiconductor superlattice.

## Optoelectronics

The ordinary semiconductor laser diode is a p-n junction (Ref 17). Electrons and holes combine in the active region and emit photons whose energy is approximately the gap energy. We have remarked that GaAs and the III-Vs are particularly effective not only because of high electron mobilities but because, unlike in silicon, the radiative recombination transition probability is large. When the density of electrons exceeds the thermal equilibrium number, a light wave of the gap energy and frequency ( $\nu = E_g/h$ ) traveling through the active region induces electron-hole annihilation radiation in the same phase. Feedback is provided by cleaved mirrors, which reflect most of the light, and if the round-trip amplification exceeds the losses, laser action occurs, leading to strong emission. Because of its 1.5-eV energy bandgap, a GaAs laser operates at around 0.8 micron (near infrared). The minimum loss in optical fibers used in communications systems occurs at about 1.5 microns. Visible light is in the range 0.4 to 0.7 micron. Thus one needs semiconductor lasers operating over a range of frequencies. The III-V compounds and DBQW and superlattice devices can be tailored to that need (Ref 17). The III-Vs, in binary, ternary, and quaternary compounds, present a broad continuum of bandgaps. By choice of materials and concentrations, doping, by adjusting the thickness of the layers in DBQWs and superlattices (Equation 1), MBE-grown III-V epitaxial structures allow for the physical properties that now make possible efficient optoelectronic devices. For example, AlGaAs laser diodes, made by MBE on large-diameter wafers, are now mass produced for pick-ups for compact discs and video disks. Photodetectors are

another application. At the Sapporo conference A.Y. Cho of Bell Labs discussed multiple quantum well GaAs/Al<sub>x</sub>Ga<sub>1-x</sub>As photodetectors responsive to 3- to 10-micron radiation whose detectivities are comparable to HgCdTe detectors (Ref 18). Madhukar (Ref 19) has written a useful overview of the materials and crystallographic principles encountered in the fabrication of lattice-matched modulated semiconductor structures.

## Nonlinear Optics

III-V superlattices are particularly powerful nonlinear optical mixers (Ref 15). This can come about from band-filling and from excitonic processes. For high energy photons it can come from umklappprozesse between minizones, but more importantly, even within one minizone. One process we can understand from the foregoing discussion is as follows. Electromagnetic waves cause the momentum of electrons and holes to oscillate at the applied frequency (Equation 2). For parabolic energy bands with effective mass  $m$ , as for free electrons, the energy is quadratic in  $k$ , as in Equation 4. From Equation 3, the velocity is then  $\hbar k/m$ , linear in  $k$ . In such a material, carriers oscillate at purely the applied frequency and there are no nonlinear overtones. Deviations from energy band parabolicity generate anharmonic response. In superlattices this is enormously enhanced by the minizone structure, as is made clear graphically in Figure 8. Bimberg and Christen (Ref 20) and Gnutzmann and Clausecker (Ref 21) discuss the optical properties of quantum wells and superlattices. We shall return to this soon.

## CONFERENCE REVIEW

### Growth Kinetics

Y. Horikoshi and M. Kawashima of NTT Electrical Communications Laboratories coauthored an invited paper on "Migration-Enhanced Epitaxy of GaAs and AlGaAs" (Ref 22). Heterojunctions grown by MBE and MOCVD suffer from two problems that deteriorate device characteristics. One is that the interfaces are rough on the atomic scale, with a large number of atomic steps. Interface roughness, for example, increases the threshold current of laser diodes (the current at which the gain balances the loss and above which laser action results). The other problem is that growth temperatures are so high (500 to 600 °C) as to cause considerable diffusion of impurity atoms, especially p-type impurities. Sharp impurity profiles are synonymous with narrow wells. Migration-enhanced epitaxy (MEE) solves both of these problems (Ref 13). With MEE, GaAs substrate temperature can be kept as low as 200 °C (and AlGaAs at 300 °C (Ref 13)). In ordinary MBE and MOCVD, GaAs and AlGaAs are grown in "As-stable conditions." Ga and Al atoms deposited on the surface immediately react with As and are immobilized in islands of GaAs and AlAs, which attach to bonds of the underlying layer. In MEE the As flux is turned off during Ga and Al deposition. This greatly enhances surface mobility of the group III elements, smoothes surfaces, and allows reduction of substrate temperature. MEE can be applied to any growth method.

S. Koshiba et al., of the Institute of Industrial Science, University of Tokyo, reported on "X-Ray Study of Growth Interruption Effects on GaAs/AlAs Superlattice" (Ref 23). Two superlattice samples with the same  $(\text{GaAs}/\text{AlAs})_{120}$  structure were grown epitaxially by MBE on substrates at 600°C. One sample was a control; on the other, growth was interrupted for 60 seconds at every AlAs/GaAs interface and for 30 seconds at every GaAs/AlAs interface. X-ray measurements were then carried out at the Photon Factory of the National Laboratory for High Energy Physics, Tsukuba-shi, because a high intensity beam of variable wavelength was needed. Anomalous scattering of x rays with energies just below the K absorption edges of Ga and As was utilized, and the (002), (004), and +1 and -1 superlattice satellite peaks were measured. For the latter in particular, which appear on both sides of the (002) 0th peak, a high intensity beam is necessary. It had been reported previously, using other and less direct detection methods, that growth interruption at each interface improves heterointerface quality (Ref 24). The present study shows why. Under normal, uninterrupted growth, interface surfaces are irregular because of islands of GaAs. During the interruption phase of the current method, these islands coalesce and/or reevaporate. This shows up as thinner layers, more uniform in thickness, and a more regular single periodicity for the structure as a whole.

W.T. Tsang, AT&T Bell Laboratories, was invited to lead us "From Chemical Vapor Epitaxy to Chemical Beam Epitaxy" (Ref 25). Pressure in the reactor is typically greater than  $10^{-2}$  Torr and up to atmospheric in CVD. Chemicals to be deposited reach the substrate surface by diffusion. As was mentioned earlier, in the

HISTORY section, by reducing the pressure in the reactor to less than  $10^{-4}$  Torr, molecular mean free paths are increased to greater than the source-inlet-to-substrate distance and deposition is by a molecular beam. This and the substitution of all gas sources for both group III and group V elements are the fundamentals of CBE (Ref 11,25), which is similar to gas-source MBE. It has some definite advantages. Because of the low gas density, in-situ monitoring is possible, by RHEED oscillations or other techniques. Similarly, it is compatible with etching, ion-beam milling, ion implantation, and other vacuum processes. Beams can be turned on and off fast; CBE is capable of submonolayer ( $<0.05$  monolayer) switch-in and switch-out. Tsang discussed an avalanche photodiode (APD) with the highest reported bandwidth (8 GHz) and the highest gain-bandwidth product (70 GHz) of any III-V APD. This is a multilayer InP/InGaAsP/AlGaAs separate-absorption-graded-multiplication (SAGM-APD). A hybrid method has been used to produce 1.3- $\mu\text{m}$  GaInAsP/InP Distributed Bragg Reflector (DBR) lasers, employing base wafers grown by CBE and Fe-doped InP lateral current blocking grown by MOCVD. Very thin base bipolar transistors, optical waveguides, optical etalons, field effect transistors (FETs), and metal insulator semiconductor field effect transistors (MISFETs) have been produced. Reference 25 contains numerous figures and copious references.

Laser light can promote selective growth and selective doping, enhance growth kinetics, and improve the quality of epitaxial layers and heterointerfaces by enhancing surface migration (Ref 26). K. Nagata et al. of the Quantum Materials Research Laboratory, Frontier Research Project, RIKEN, Institute of Physical and

Chemical Research, presented RHEED data on "Photo-Assisted Chemical Beam Epitaxy of GaAs" (Ref 27). They show that Ar<sup>+</sup> laser irradiation increases the rate of decomposition of triethylgallium (TEGa) much more on the As planes than on the Ga planes. The radiation also increases the surface mobility of Ga adatoms and TEGa molecules.

The show-stopper of MBE-V, from the standpoint of the U.S./Japan high tech race, was the invited talk "MBE as a Production Technology for HEMTs and Related Devices," by K. Kondo (Ref 28) of Fujitsu Ltd. Discrete high electron mobility transistors (HEMTs) for ultra-low-noise microwave amplifiers are already commercially available. In Japan, satellite TV receivers contain HEMTs. Fujitsu is going into production by MBE of AlGaAs/GaAs HEMT LSIs for ultra-high-speed digital applications, including 4-k gate logic and 16-kbit static RAM LSI circuits. Depositions are made on three 3-inch wafers simultaneously. In-situ RHEED monitoring makes possible precise control of growth rates. Epitaxial layer thickness, carrier concentration, and alloy composition are uniform over the entire area of the three wafers to within 1 percent. Density of oval defects is less than 10 cm<sup>-2</sup>. Fujitsu is continuing parallel development of an MOCVD pilot production line, just in case that proves superior in throughput.

The Fourth International Conference on Metalorganic Vapor Phase Epitaxy was held at Hakone, Japan, in May 1988. H. Kukimoto, Imaging Science and Engineering Laboratory, Tokyo Institute of Technology, reviewed for MBE-V the presentations at Hakone on metalorganic chemical vapor deposition in his invited talk "MOCVD—Current State and Future" (Ref 29). The Hakone conference was reviewed by Bottka and Gaskill (Ref 30) in

the *Scientific Information Bulletin*. MOCVD has been used to grow III-Vs, such diverse II-VIs as the narrow gap CdHgTe and the wide gap ZnSe, and the I-III-VI<sub>2</sub> materials CuGaS<sub>2</sub>, CuGaSe<sub>2</sub>, and CuAlS<sub>2</sub>. Other materials successfully grown by MOCVD include GaN, AlN, SiC, Al metal films for wiring, oxide dielectric films, and high T<sub>c</sub> superconducting films (but not universally successfully so far; see below). As for sources, the same problems confront MOCVD as MOMBE and CBE—purity and toxicity. Only TMGa is sufficiently pure at present. But of course this obstacle will be surmounted as usage increases.

In concentrations of just a few ppm the group V hydrides are lethal. In some localities in the United States (Seattle and Silicon Valley) usage is already bumping up against municipally regulated limits, and waste disposal is difficult. The Japanese also will have to deal with the grave environmental risk of large quantities of highly toxic, high pressure arsine gas in commercial operations in densely populated urban areas.

Sources can be decomposed thermally, photochemically, or by glow discharge. Low temperature growth is essential for the II-VIs to reduce interdiffusion at interfaces and to control conductivity of ZnSe and ZnS. Low growth temperatures are made possible by laser irradiation and/or digital source supply in atomic layer epitaxy. Perhaps the major attraction of MOCVD is its mass production capability. Several 2- or 3-inch wafers have now been grown at a time, with high uniformity in thickness and carrier concentration, both in one wafer and from run to run. On the other hand, wafers are expensive, and as noted previously, MOCVD precludes in-situ RHEED monitoring. Also it is not clear that there is a need for large-scale production. The compact disc market is easily

supplied by a small operation. Kukimoto projected MOCVD-produced large-area devices: ultra-large-area solar cells and electroluminescent display panels.

### Si-Ge Heterostructures

While the III-Vs dominate optoelectronics, Si is the workhorse of the electronics industry. It is therefore necessary to investigate group IV superlattices and, for hybrid technologies, III-V/IV heterostructures. Among their other virtues, the III-Vs have closely matching lattice constants, making epitaxy easy. In group IV there are fewer alloys, and their lattice spacings don't match. (The mismatch between Si and Ge is 4.2 percent.) Lattice mismatch can be accommodated by dislocations, which damage electronic performance, and by lattice strain (Ref 13). The initial atomic layers of a deposited film will strain to match the substrate structure, but as deposition continues at a critical thickness dislocations form. This suggests growing superlattices of alternate layers of compensating positive and negative strain, each layer thinner than the critical thickness for dislocation formation. An arrangement that meets this criterion nicely is Si and Ge on Si (001) substrate (Ref 31). Si/Ge strained layer superlattices (SLSs) were a major topic of MBE-V.

K. Miki et al. of the Electrotechnical Laboratory, Tsukuba, spoke on "Ge<sub>m</sub>/Si<sub>n</sub> Strained-Layer Superlattices Fabricated by Phase-Locked Epitaxy" (Ref 32). Phase-locked epitaxy is a grand phrase; in the current context it comes down to alternate Ge and Si depositions monitored in situ by RHEED intensity oscillations. As the desired number of monolayers of each constituent is laid down, the flux of that source is turned off and the other turned on.

The authors have confirmed that one RHEED oscillation represents one monolayer. At six layers of Ge on Si (001) the oscillations disappear and the RHEED pattern degenerates to spots. It has been independently determined (Ref 33) by Rutherford backscattering that the critical thickness for dislocation formation is six layers of Ge on Si. Figure 9 shows RHEED intensity oscillations during the Si<sub>n</sub>Ge<sub>m</sub> formation. Ge<sub>m</sub>/Si<sub>n</sub> SLSs have been fabricated up to a total thickness of 240 monolayers, with (m,n) = (1,4) and (4,16). Twenty layers of Si are deposited on top. A notation for such a structure is Si<sub>n</sub>/(Ge<sub>m</sub>/Si<sub>n</sub>)<sub>ω</sub>/Si (001).

Apart from the challenge of doing it and the joy of understanding it, why does one want to make Si/Ge superlattices anyway? In the section titled Superlattices we looked at the broadening into minibands when there is tunneling between wells in a superlattice. The thinner the barrier and the less the difference between energy gaps in the two materials (depending upon band offset), the more the wavefunctions penetrate and overlap and the broader the minibands. Of course as the barrier layers are made thinner and further apart, the minibands must revert to the energy band structure of the host crystal, but somehow perturbed by the superimposed superlattice periodicity. Figures 8b and 8c showed how to fold back and forth between the central zones and extended zones of the atomic and superlattice reciprocal lattices. The point to be emphasized here is that in so doing, electronic states arising from different atomic levels, states that occurred at very different momenta in the ordinary Brillouin zone, may be folded to almost the same momentum in the superlattice Brillouin zone, depending on the superlattice periodicity (Ref 21). This has important consequences for the optical properties. It allows

absorption and emission of photons, hence coupling between electronic and optical

response, at energies at which such coupling could occur only inefficiently in pure Si or Ge. Box 2 explains how.

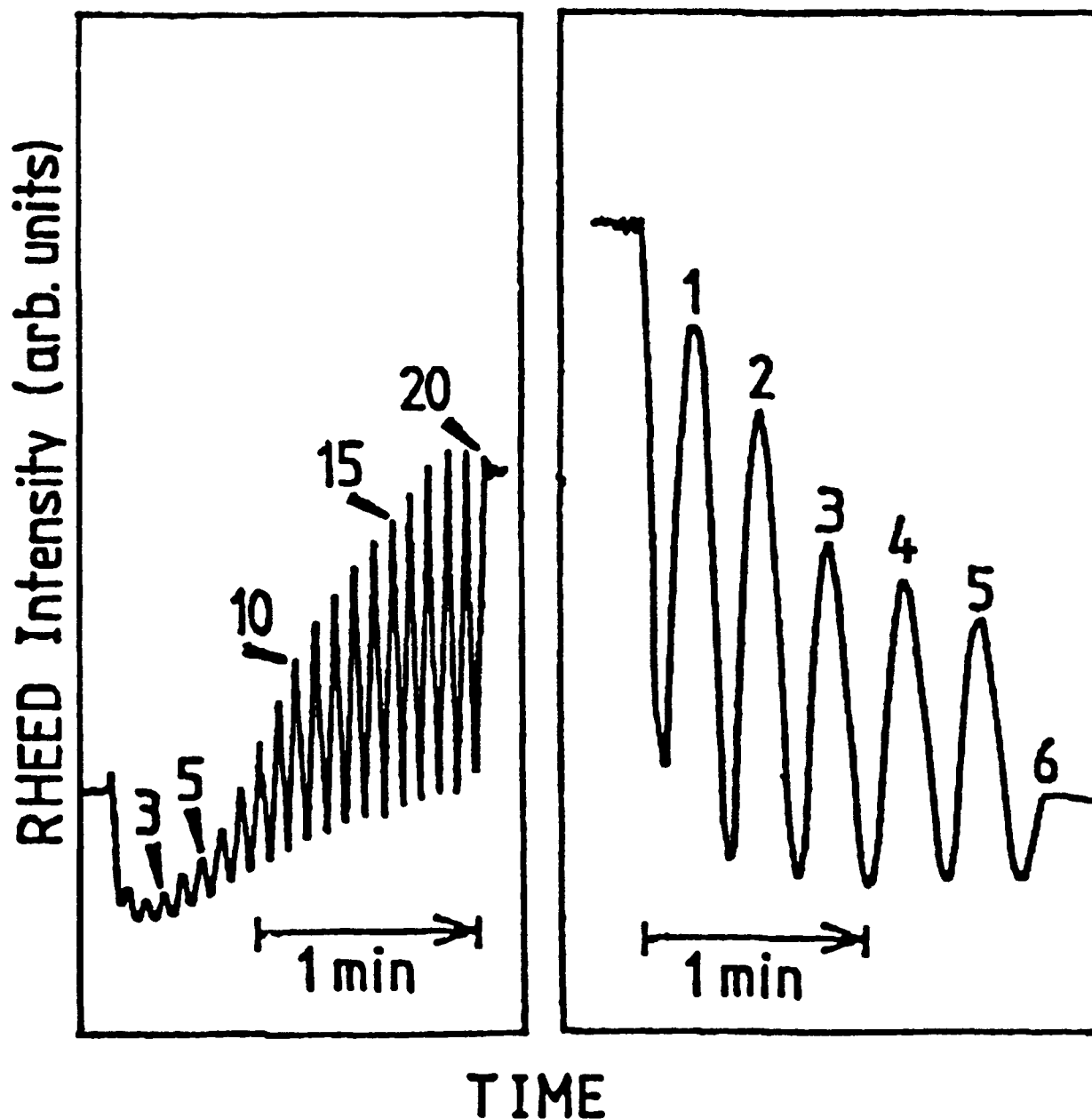


Figure 9. RHEED intensity oscillations during the heteroepitaxial deposition of a Si/Ge superlattice onto Si (001). One intensity oscillation occurs during the deposition of a single monolayer (after Ref 32). The left panel shows 20 layers of Si deposition, and the right panel shows 6 layers of Ge deposition.

## Box 2. Band Folding and the Optical Properties of Superlattices

Figure 10 depicts the band structures of Si and Ge. In both cases the valence band maximum is at  $k = 0$ , the center of the Brillouin zone. In neither case is the conduction band minimum at the origin. In Si the minimum is out near (but not at) the zone boundary in the  $\langle 100 \rangle$  direction; in Ge it is at the zone boundary in the  $\langle 111 \rangle$ . The minimum gap, the "indirect gap," in Si is 1.08 eV; that in Ge is 0.66 eV. Now suppose we have excited some electrons into the conduction band of either material. They will gravitate, perhaps through phonon emission, to the minimum energy states near the zone boundary. Can an electron and hole now recombine and radiate a photon (or conversely, can a photon whose energy is that of the indirect gap,  $E_g$ , be absorbed through creation of a hole/electron pair)? The answer is: "Only if a phonon is also radiated (or absorbed)" (see Figure 11). In the process both energy and momentum must be conserved. Suppose we try to conserve energy and (crystal) momentum without wasting some of the energy on the phonon. We then must have

$$E_g = E_{\text{photon}} \quad (\text{B2-1})$$

$$E_g/\hbar c = k_{\text{phot}} = k_d \quad (\text{B2-2})$$

where  $k_d$  is the difference in crystal  $k$  vectors between the valence band maximum and the conduction band minimum. Now  $c$ , the velocity of light, is a very big number, and for the gap energies of 1 eV or so the photon wavenumber of Equation B2-2 is negligibly small. Only closely vertical transitions can occur with photon absorption or emission alone.

If a phonon is involved, Equations B2-1 and B2-2 become

$$E_g = E_{\text{photon}} + E_{\text{phonon}} \quad (\text{B2-3})$$

$$E_g/\hbar c = k_{\text{photon}} + k_{\text{phonon}} = k_d \quad (\text{B2-4})$$

The phonon energy is

$$E_{\text{phon}} = \hbar \omega_{\text{phon}} = \hbar v_s k_{\text{phon}} \quad (\text{B2-5})$$

The velocity of sound,  $v_s$ , is relatively low, and so most of the crystal wavenumber (or momentum) difference  $k_d$  can be taken up by the phonon, making the process possible. But still, energy is wasted in the phonon, and the probability of the process is reduced because an additional particle is involved. The statistics are different for electron-hole recombination than for creation.

(continued)

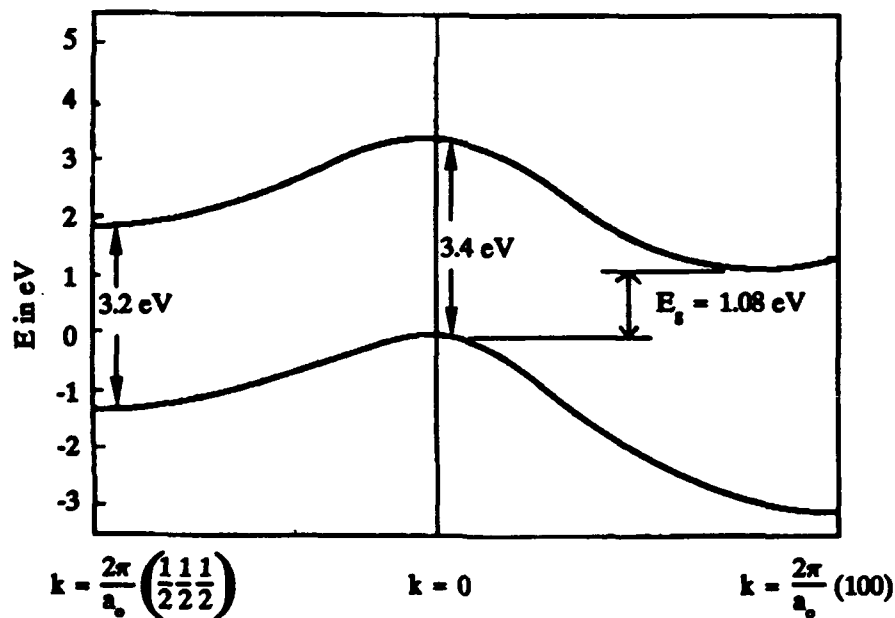


## Box 2. Continued

But with the superlattice the wavenumber of the conduction band minimum can be folded back to the origin, as in Figure 8, allowing direct optical transitions, with no phonon!

It does not come for free [see Bimberg and Christen (Ref 20) and Gnatzmann and Clausecker (Ref 21)]. The Bloch wavefunctions of the electron and hole in the superlattice are modified from those of the pure material. The transition probability for recombination involves a matrix element between wavefunctions. Though the transition is vertical, the matrix element is reduced by the mixing. One can understand this by the following argument. Suppose to fold a  $k$  of a band extremum into the origin (or anyplace else to coincide with another band extremum) we must create a superlattice of large period in real space. This will make a very diminished Brillouin zone and make all states almost vertical, to be sure. But clearly as the superlattice period gets larger and larger, as the inserts are placed further and further apart, the material must be more and more like the unaltered host. In the limit the matrix element must go to that of the host.

Of course, the phonon spectrum is also folded back (as would be the magnon spectrum in a magnetic superlattice, and every other elementary excitation of the periodic array). Thus will the superlattice be manifested in its Raman spectrum.

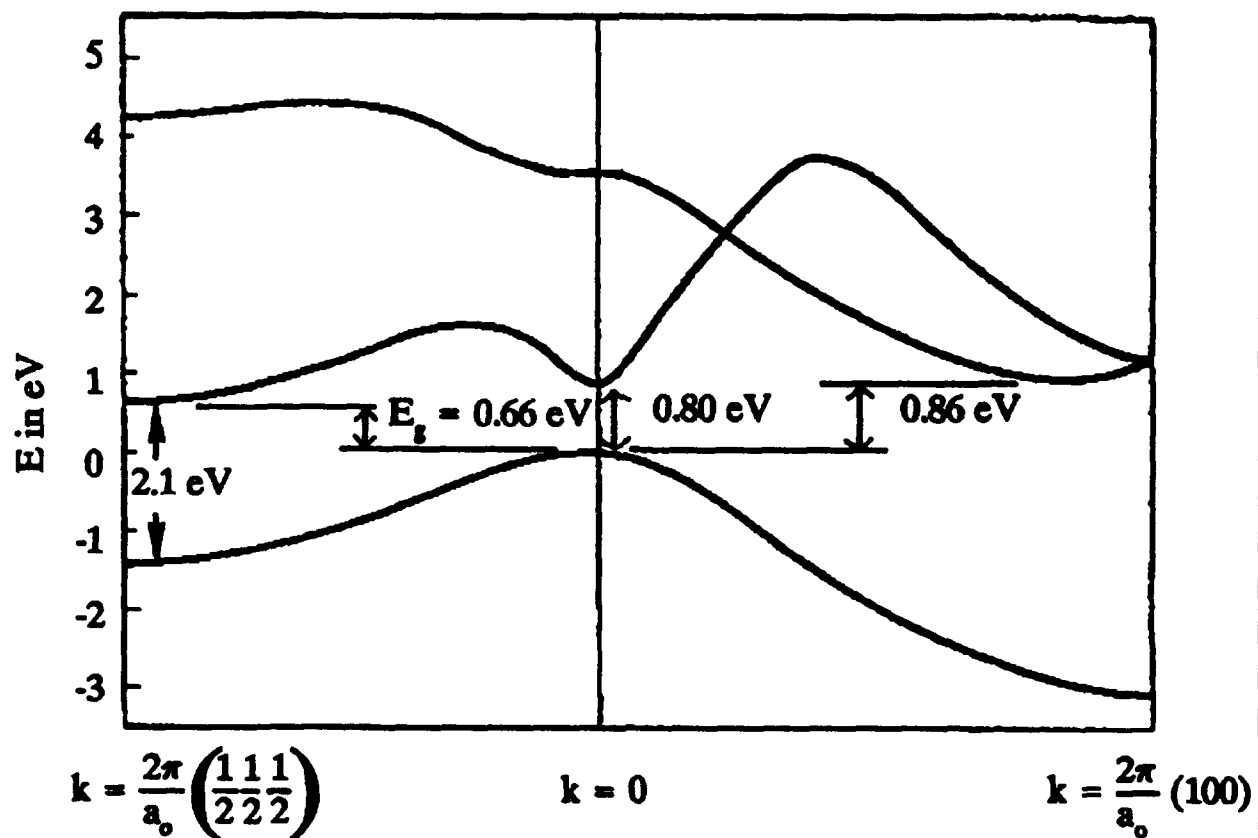


- (a) The band structure of Si. The maximum of the valence band is at  $k = 0$  (a small spin-orbit splitting is shown). The minimum energy of the conduction band occurs at a state along the  $\langle 100 \rangle$  but not at the zone boundary in that direction. The indirect gap is  $1.08 \text{ eV}$ .

Figure 10. Band structure.

(continued)

Box 2. Continued

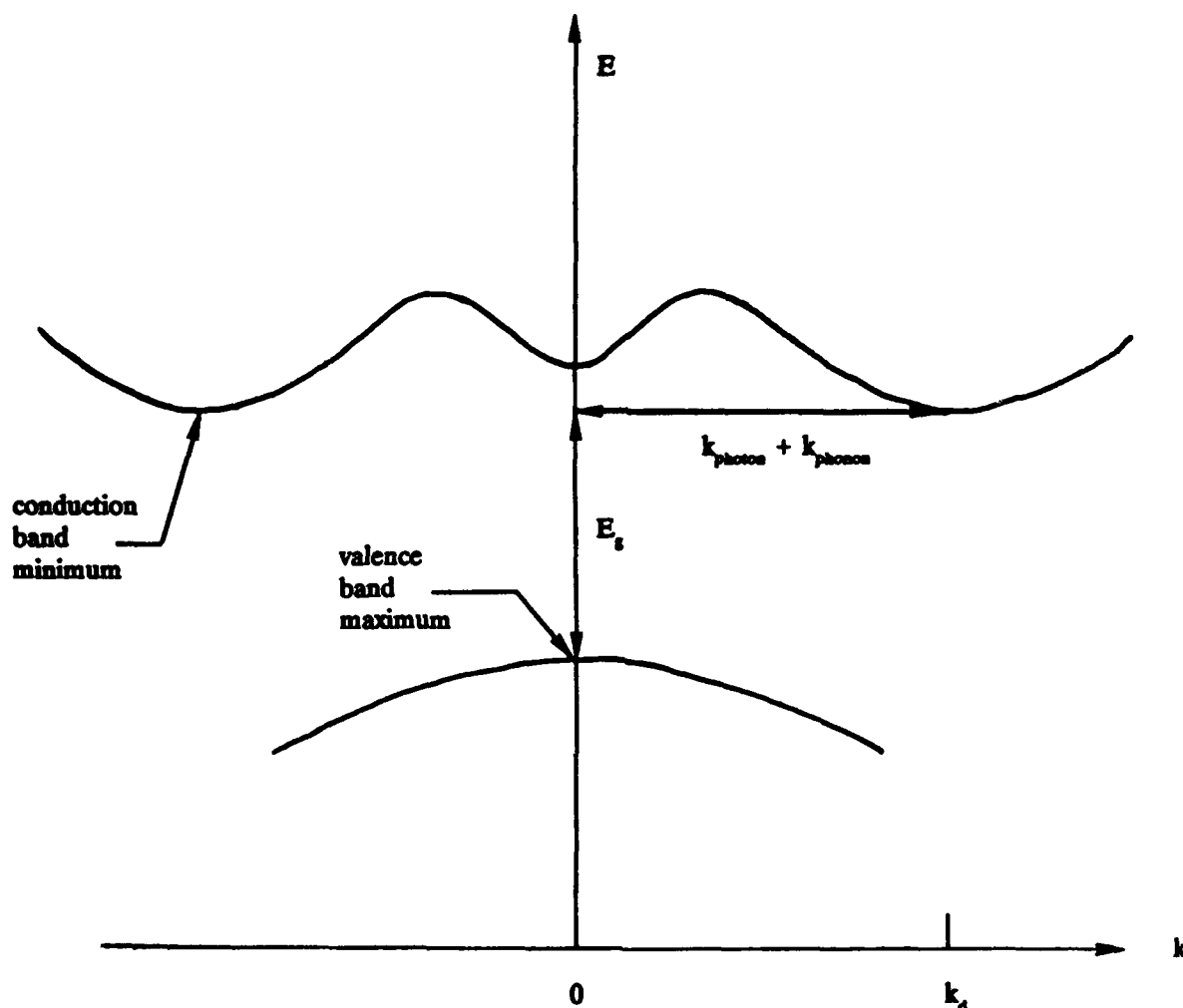


- (b) Band structure of Ge. Again the spin-orbit split maximum of the valence band is at  $k = 0$ , and the minimum of the conduction band is somewhere else, in this case at the zone boundary in the  $\langle 111 \rangle$ . The indirect gap is  $0.66$  eV.

Figure 10. Continued.

(continued)

## Box 2. Continued



**Figure 11.** Conservation of energy and momentum. In an optical transition, the energy of the photon and of all phonons radiated must equal the energy lost by the electron-hole pair in annihilation. The momenta of the photon and phonons must also equal the net momentum lost by the electron and hole. Photons have negligible momentum, and so in nonvertical transitions emitted phonons must take up the momentum. This significantly reduces efficiency. But in a superlattice of proper period the maximum and minimum of the valence and conduction bands can be made to be at nearly the same wave vector. The transition is then vertical and no phonon is emitted in the radiation process. But the transition probability, the probability of radiative recombination, may be small.

All of this is discussed in the invited paper by G. Abstreiter et al., **"Silicon/Germanium Strained Layer Superlattices"** (Ref 34), and other papers by the Abstreiter group (Ref 34) at the Technical University of Munich. An important point to note is that, because of the dilatational and compressive transverse strains, band structures of the materials of the superlattice differ from those of the bulk. For example, with (100) interfaces, the uniaxial strain splits the sixfold degenerate conduction band and the heavy and light hole valence bands of Ge; it leaves the band edge symmetries intact but lowers the conduction band edge of Si. Abstreiter finds the critical thickness for dislocation formation to be four atomic layers. Probably critical thickness is not such a sharply defined quantity, and the difference between the Abstreiter and the Miki (Ref 32) and Bevk (Ref 33) result (six layers) is one of criterion, of measurement method, and of particular circumstances. The Abstreiter paper did not arrive in time for the conference workbook but will appear in the published proceedings; it is recommended by the present authors.

S.J. Chang et al. (Ref 35) of the University of California, Los Angeles recounted their **"Study of Ultra Thin Ge/Si Strained Layer Superlattice"** by Raman scattering spectroscopy. The superlattice period is determined by observation of folded acoustic phonon peaks. Optical phonon frequencies are found to depend strongly on superlattice period. Since Ge-Si vibrations can come only from interfaces and from interfacial diffusion, the intensity of peaks from this bond is a measure of the superlattice period (the longer the period, the less the intensity) and of diffusion.

It would be desirable to have a non-conducting substrate on which to grow Si films, or if not that, a way of growing an epitaxial, lattice-matched insulating layer on Si. Sapphire is such a substrate, but it is

expensive. K. Sawada et al. described a promising solution in their talk **"Metal-organic Molecular Beam Epitaxy of  $\gamma$ -Al<sub>2</sub>O<sub>3</sub> Insulator Films on Si with Laser Irradiation"** (Ref 36). This group has grown  $\gamma$ -Al<sub>2</sub>O<sub>3</sub> thin films on (100) Si by CVD at 1,000 °C and on (100) and (111) Si by MOMBE at 720 °C. Now by laser-assisted MOMBE they are able to produce epitaxial  $\gamma$ -Al<sub>2</sub>O<sub>3</sub> films on both (100) and (111) Si at much reduced substrate temperatures (450 °C) and at three times the growing speed.  $\gamma$ -Al<sub>2</sub>O<sub>3</sub> films have a high electrical resistivity.  $\gamma$ -Al<sub>2</sub>O<sub>3</sub>/Si should be a practical insulating substrate. Stacked structures of Si/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub>/Si are now being attempted.

### GaAs on Si

Since GaAs and the III-Vs are the materials for lasers and optical devices and Si is the stuff chips are made of, a mating was natural. But the issue is strained, with dislocations induced by lattice mismatch (the lattice constant of GaAs is about 4 percent larger than that of Si). Y. Horikoshi, the originator and advocate of MEE for III-V heterojunctions (Ref 22), shows its efficacy in growing GaAs on Si. W. Stolz, Y. Horikoshi, and others of NTT Electrical Communications Laboratories spoke on **"Optimized Growth Start and Controlled Formation of Misfit Dislocations for Heteroepitaxial GaAs on (100) Si Grown by Migration-Enhanced Epitaxy"** (Ref 37). One must avoid the formation of a stable As layer on the Si. A stable As layer forms at high temperature (600 °C), so the Si is kept at 300 °C. There is already a metastable cover of As on the Si from the heating of the As effusion cell after the high temperature Si anneal. Growth is initiated under Ga-dominated conditions. Ga is supplied first to the Si surface, and then only the least amount of As<sub>4</sub> is turned on to allow GaAs epitaxial layer growth by MEE.

In the evening session H. Kroemer et al., University of California, Santa Barbara, discussed "GaAs on Si and Related Systems: Problems and Prospects" (Ref 38). Kroemer spoke on the antiphase domain problem briefly and the dislocation problem at some length. Either of the two fcc Si sublattices can be the sites of the Ga or of the As sublattice. So there is every reason to expect antiphase domains to be a major problem. They are not. By misorienting the (100) Si substrate slightly a very high degree of order is achieved, and nobody knows why. Dislocations are a more important problem. Almost all devices require thicker GaAs than the 4- to 6-atomic layer critical thickness. A 4-percent mismatch requires a dislocation about every 25 atomic rows. By symmetry the Burgers vector must lie in the  $\langle 110 \rangle$  parallel to and close to the interface, and there must be two orthogonal sets of dislocation arrays. In each set dislocations are spaced about 100 Å apart. A dislocation can terminate only on a surface; the dislocations bend away from the interface plane and into the GaAs. Dislocations with the same Burgers vector approach each other and mutually annihilate. Hence dislocation density decreases with increasing distance from the substrate into the GaAs (but not rapidly enough). Kroemer estimates a colossal dislocation density of  $4 \times 10^{10} \text{ cm}^{-2}$  threading into the GaAs,  $10^6$  greater than in bulk material ( $\sim 10^4 \text{ cm}^{-2}$ ). Kroemer shows that the asymptotic density of threading dislocations with increasing distance from the interface is independent of the number of dislocations near the interface and falls off only inversely with distance. Because of the difference in thermal expansion coefficients of GaAs and Si, only about 4  $\mu\text{m}$  of GaAs can be deposited without danger of cracking on cooling. In the upper 2 or 3  $\mu\text{m}$ , pair annihilation has reduced dislocation density to about

$10^4 \text{ cm}^{-2}$ . Remarkably, quantum well devices and heterostructure bipolar transistors can operate satisfactorily with this number of dislocations threading through them,  $10^4$  times the bulk value. For a variety of reasons, dislocations in superlattices do not do as much harm as do dislocations in single-phase systems.

Silicon diodes and transistors started as discrete elements two or three decades ago; today because of LSI, Si-based electronic devices permeate society--in homes, offices, factories, in transportation, communication, and defense. Optoelectronics is now in the early phase that semiconductor electronics was in a quarter century ago. Light-emitting diodes (LEDs), photodetectors, and semiconductor lasers are made only as discrete devices. The next step, the step that will expand optoelectronics from optical communication, laser printers, and compact discs into new technologies reaching everywhere in our lives, will be optoelectronic integrated circuits (OEICs). It seems that hybrid III-V/IV composite devices will play a major part.

## II-VI Compounds

We have remarked that GaAs and the II-VI group have the highest conversion efficiency as light-emitting diodes and for other optical devices. Their spectral range now extends into the visible up to 2.1 eV (green; 600 nm). But there is a need for emitters of light of higher frequency, in the blue. For this the II-VI compounds are important because of their wide bandgap. George Wright has written an excellent review of the physics of the II-VIs (Ref 39). In his opening survey talk in the plenary session, "Current State and Future Challenge in Molecular Beam Epitaxy Research," A.Y. Cho, of Bell Labs, reviewed, *inter alia*, recent developments in

the II-VIs (Ref 18). ZnSe has a bandgap of 2.67 eV. It is grown on GaAs substrate because its mismatch to GaAs is only 0.25 percent, but in a Ga-stabilized environment it nucleates in islands. It has been discovered that nucleation is more ordered when grown under As-stabilized conditions (Ref 40). ZnSe/n-GaAs MISFETs, while not yet satisfactory devices, are showing promise.

Cho described optically pumped lasers emitting in the orange near 600 nm at room temperature. These are  $\text{Cd}_{0.25}\text{Zn}_{0.75}\text{Te}/\text{ZnTe}$  superlattices grown on GaAs. While the lattice strain between CdTe and ZnTe is large (6 percent), at  $\text{Cd } x = 0.25$  the lattice strain is only 1.5 percent. The lasing device consists of 15 periods of 50-Å-wide  $\text{Cd}_{0.25}\text{Zn}_{0.75}\text{Te}$  wells and 100-Å ZnTe barriers grown on a GaAs substrate intermediate buffer layer to accommodate the lattice mismatch.

HgTe films have been grown on (100) GaAs with a record high electron mobility at 80 K of  $92,200 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$  (Ref 41). Now, using large Hg effusion cells,  $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$  epitaxial layers more than 15  $\mu\text{m}$  thick, uniform in thickness over a 2-inch CdTeSe substrate, and with  $\delta x$  only  $\pm 0.005$  have been grown (Ref 42). In the II-VI compounds the free carrier concentration is not easily controlled. Because of tendencies toward nonstoichiometry, ZnS tends to be n-type and ZnTe tends to be p-type. Depending upon growth conditions more than upon doping, HgTe, CdTe, ZnSe, and HgCdTe can go either way. Epitaxial layers of  $\text{Hg}_{0.66}\text{Cd}_{0.34}\text{Te}$  12  $\mu\text{m}$  thick have been grown on CdTe (111) under Te-rich conditions, creating Hg vacancies so that the films are p-type. B and other group III ions are implanted ( $\sim 250 \text{ kV}$ ;  $10^{13}$  to  $10^{14} \text{ cm}^{-2}$ ) to form a surface n layer (the implanted group III elements take the Hg, group II site), and a p-n junction.

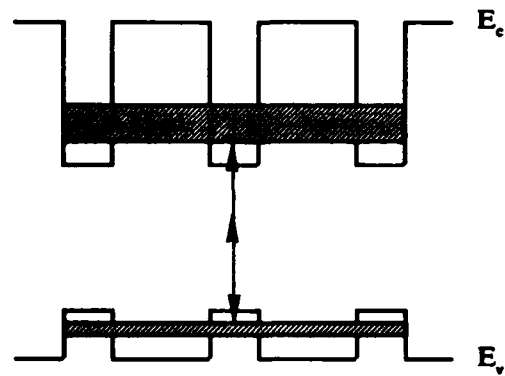
Several groups reported success in growing doped n- and p-type epitaxial films. M. Kitagawa et al. of Sharp Central Research Labs spoke on "Homoeptaxial Growth of Low-Resistivity Al-Doped ZnS Single Crystal Films by MBE" (Ref 43). When the ability to control conduction type and conductivity is mastered, ZnS will be a useful material for light-emitting devices in the blue to ultraviolet. With an Al concentration of  $4.6 \times 10^{19} \text{ cm}^{-3}$ , Kitagawa et al. report a room temperature electron concentration of  $3.9 \times 10^{19} \text{ cm}^{-3}$ ; a resistivity of  $2.2 \times 10^{-3} \Omega\text{cm}$ ; and the highest Hall mobility in heavily doped ZnS,  $74 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$ . Presumably about 85 percent of the Al behaves as a shallow donor, and the doped material is degenerate.

H. Cheng et al., of 3M, reported on "Growth of p- and n-Type ZnSe by MBE" (Ref 44). Ga, In, and Al substitute on the Zn site, as in the work of Kitagawa et al. above. Another approach is incorporation on the site of the group VI element. Ohkawa et al. (Ref 45) and now Cheng et al. show that Cl is a well-behaved donor and have grown n-type ZnSe with a carrier concentration greater than  $10^{19} \text{ cm}^{-3}$ . The next hurdle is the production of p-type material. N, Li, and Na substitutions have been tried. In small amounts Na goes in as a shallow acceptor but fails to convert the ZnSe to p-type. Li appears more promising. The majority carriers in ZnSe-Li are indeed holes, and hole concentration increases with increasing Li up to about  $8 \times 10^{16} \text{ holes cm}^{-3}$  at about that same Li doping density. But further doping causes the hole concentration to decrease. This is because of compensation. Another problem with Li is its large diffusivity. Attempts to concentrate the Li in a narrow layer resulted instead in a uniformly doped sample.

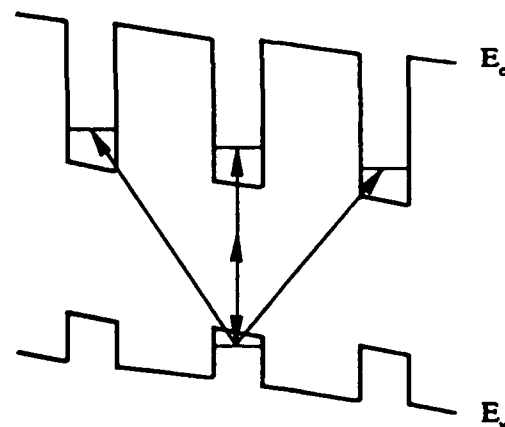
PAMBE is photon-assisted MBE. J.D. Benson et al., Georgia Technical Research Institute, in "Properties of Undoped and Sb-Doped CdTe Surfaces Prepared by Conventional and Photon-Assisted Molecular Beam Epitaxy" (Ref 46), show what the light does. Sb can occupy either Cd or Te sites. Photoillumination increases the concentration of Sb on the Te sites and increases the concentration of Te vacancies.

### Electric Field-Induced Localization

M. Voos, Ecole Normale Supérieure, described a line of pretty optics research in "Recent Developments in Optical Processes in Quantum Wells and Superlattices: Many Body Effects and Field-Induced Localization" (Ref 47). Imagine a superlattice, and an adjustable electric field along  $z$ , normal to the planes. In Figure 12 we again diagram the superlattice band structure, but now with only one electron and one hole subband shown for simplicity. At zero electric field (Figure 12a), one observes inter-subband optical transitions between the ground valence ( $h_1$ ) and conduction ( $e_1$ ) subbands. The optical bandwidth reflects the electron and hole subband bandwidths. At large electric fields, depicted in Figure 12c, subband energies evolve into Stark ladders. The shift in energy between successive wells by the field,  $0.5(eE)(L)$ , exceeds the subband bandwidths and tunneling is inhibited. The wells are uncoupled and isolated, and carriers are localized. There is a blue shift in the optical absorption energy and in photoluminescence. At intermediate fields one should observe satellite optical transitions that are oblique in real space, as shown in Figure 12b.

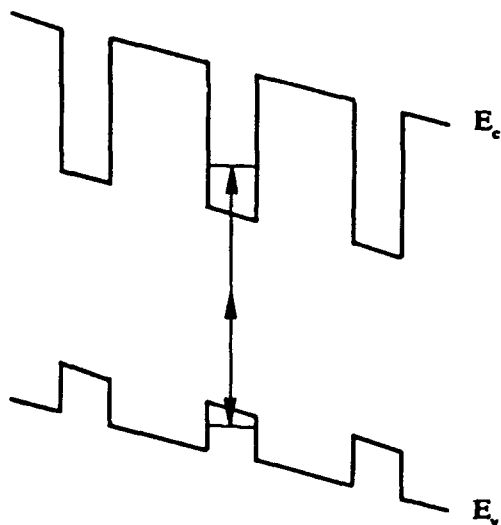


(a) A superlattice, with only the lowest electron subband,  $e_1$ , and highest hole subband,  $h_1$ , shown. Optical transition bandwidth reflects subband bandwidth.



(b) As the electric field, perpendicular to the superlattice planes, is increased, the subbands evolve toward Stark ladders. At intermediate fields both transitions within one GaAs layer and satellite optical transitions between adjacent layers should be observed.

Figure 12. Electric field localization (after Ref 47).



- (c) At high fields the wells are isolated and wavefunctions localized. Transitions are confined again to individual wells and between the equally spaced levels of Wannier-Stark ladders.

Figure 12. Continued.

### High Electron Mobility Structures

The inspiration that brought about high electron mobility transistors (HEMTs) was the recognition that the very high electron mobility of GaAs could be harnessed to advantage in a heterojunction. Ionized dopants are needed to provide carriers, but scattering by these ions reduces mobility. (An exception is the InAs/GaSb heterostructure; here electrons and holes originate from electron transfer.) The idea then is to situate the donors within the barrier layer, say AlGaAs, of a heterojunction. Electrons thus provided can move unscattered (or more accurately, less scattered) by

the stray electric fields of the impurities, parallel to the interface in the high mobility pure GaAs channel. Making it work and marketing it are something else again (Ref 13). Fujitsu sells HEMTs. Now A.C. Gossard et al., University of California, Santa Barbara, have performed detailed comparative studies of rather complex heterostructures, with a view not so much toward producing an immediate device but rather toward analyzing the circumstances that will ultimately allow production of the best devices. In "Growth and Doping of Heterostructures for High Electron Mobilities" (Ref 48), Gossard described numerous heterostructures, with various barrier setback layers, modulation-doped and delta- (or planar-) doped, grown at several substrate temperatures. The conclusions are rather more detailed than can be summarized here, but higher electron mobilities have been reached, the highest being  $5.0 \times 10^6 \text{ cm}^2 \text{V}^{-1} \text{s}^{-1}$ . And this is not yet the theoretical limit.

Gossard was followed by M. Shayegan et al., Princeton University, with "MBE Growth of Two-Dimensional Electron System with Extremely Low Disorder" (Ref 49), and then by J.E. Cunningham et al. of Bell Labs on "High Mobility and Density in Selectively Doped AlGaAs/GaAs Heterostructures" (Ref 50). The perfection (primarily the high mobility) of these artificially created structures is such that they have allowed the study of heretofore-unobserved fundamental properties of the many body, two-dimensional electron (or hole) gas: quantized Hall effect and the most accurate determination of the fine structure constant



(Ref 51), fractional quantum Hall effect, quantum Hall effect with even fractional filling of Landau levels, Bloch-Gruneisen freeze-out of phonon scattering, and (not yet but perhaps!) Wigner condensation.

The quantum Hall effect, though remarkable, can be understood in conventional terms. The fractional quantum Hall effect is something else again. A magnetic field is applied parallel to the planes of one of Gossard's high mobility, GaAs heterostructures (the quantum Hall effect was actually first observed in Si-inversion layers (Ref 51)). Because of the Lorentz force the electrons go in circles, cyclotron orbits with classical frequency  $\omega_c$ . Electron states within ranges  $\hbar\omega_c$  condense into degenerate clumps. The allowed states and energies are the quantized Landau levels, and as the field is increased these shift through the Fermi level. This is, of course, the origin of the well-studied  $1/H$  oscillations in the magnetic susceptibility (de Haas-van Alphen effect) and in the magnetoresistance (Shubnikov-de Haas effect). An electric field is applied parallel to the planes, say along the x-axis. The (transverse) magnetoresistance is that component of the electrical resistance along the electric field direction. (There is a longitudinal magnetoresistance measured along the electric field but with E and H parallel.) The Hall resistance is that component of the resistance along the third direction, the y-axis, again parallel to the planes but perpendicular to the electric and magnetic fields. It arises because of the Lorentz force. In Figure 13 we show measured magnetoresistance  $\rho_{xx}$  and Hall resistance  $\rho_{xy}$  versus field. In ranges of magnetic field such that the Fermi

level is located within the localized states, which do not take part in quantum transport (Ref 52), the magnetoresistance vanishes and the Hall resistance is flat. At these field strengths the Hall resistance is inversely proportional to the fine structure constant,  $\alpha$ , and to a Landau level occupation index,  $\nu$  (essentially the number of filled levels). This allowed determination of the fine structure constant. At several of the minima and flats the index of the number of levels is an integer, as it presumably must be. How can there be a nonintegral number of quantum levels? Then the fractional Hall coefficient was discovered by Tsui, Stormer, and Gossard (Ref 53). Some of the minima are accounted for only when the number index is a fraction. Tsui et al. observed  $\nu = 1/3$  and  $2/3$ ; since then the Gossard group and others have seen  $\nu = 2/5, 3/5, 4/5$ , and sequences of even fractions. Laughlin (Ref 54), in a *tour de force* of imagination, explains the phenomenon by invoking a new series of ground states of the two-dimensional electron gas, an incompressible quantum fluid, ultimately terminating in a Wigner crystal at very large magnetic field and critical Landau level filling factor. The excited states of this new quantum fluid are fractionally charged, like quarks! Who would have anticipated that a search for better HEMTs and high mobility devices would have resulted in all this? (The search for some quantum transport effects is actually much older. Fowler et al. (Ref 55) started the study of quantum transport back in 1966. But probably no one, not even Laughlin, would have had the imagination to have anticipated the fractional quantum Hall effect.)

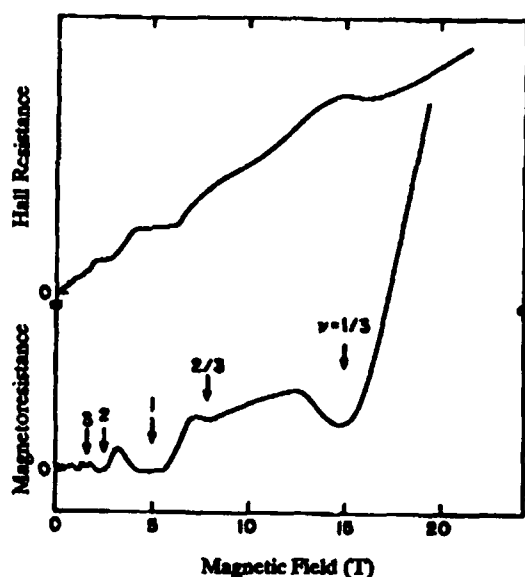


Figure 13. Quantized and fractional quantized Hall effect. Hall resistance  $\rho_{xy}$  and magnetoresistance  $\rho_{xx}$  of a GaAs/AlGaAs heterostructure versus magnetic field strength (after Ref 53).

### Low-Dimensional Structures

MBE naturally makes planar, two-dimensional arrays. How can we make wires and dots and interconnect planes with wires normal to interfaces? In a session on such structures, P.M. Petroff et al. of the University of California, Santa Barbara reported on "Band Gap Modulation in Two Dimensions by MBE Growth of Tilted Superlattices and Applications to Quantum Confinement Structures" (Ref 56); K.Y. Lee et al. of IBM, Yorktown Heights discussed "One- and Zero-Dimensional Systems: Fabrication and Characterization" (Ref 57); P.R. Pukite et al. of the University of Minnesota presented evidence for "The Meandering of Steps on GaAs (100)" (Ref 58); and K. Kanamoto et al. of Mitsubishi Electric Company spoke on "Surface Diffusion During MBE Growth of GaAs-AlGaAs Single Quantum Wells on

Vicinal Surfaces" (Ref 59). Petroff et al. (Ref 60) proposed making quantum wires by growing epitaxial films on a vicinal substrate. This allows the MBE growth of structures with composition and bandgap modulation in directions parallel and at any angle to the substrate surface. On a vicinally misoriented substrate with a regular array of straight, equidistant steps, one deposits fractional submonolayers alternately of two-compound semiconductors, say GaAs and AlAs. By this means one grows a tilted superlattice (TSL) (Ref 61). Typical misorientations are about  $2^\circ$ , and lattice steps are spaced by about 80 Å. Quantum well wires have been grown and have shown the first evidence of two-dimensional quantum confinement (to a wire) (Ref 56). Lee et al. (Ref 57) have etched the wires to produce lines and dots ranging from 0.1 to 0.4  $\mu\text{m}$ . Capacitance oscillations conform to what should be expected from the energy levels of quantum dot and quantum wire wells. One-dimensional confinement reduces electron scattering, and this should result in an increase in mobility. Fujitsu has developed prototype devices with an array of 100-Å GaAs quantum wires for fast circuitry. How about high  $T_c$  wires someday?

### High $T_c$ Superconductors

An invited talk on making high  $T_c$  superconductors by MBE described trials, not successes. But T. Terashima et al. (Ref 62), of the excellent and enterprising Bando group at the Institute for Chemical Research of Kyoto University (Ref 63), report on their success in growing single-crystal epitaxial films of  $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$  by activated reactive evaporation on (100)  $\text{SrTiO}_3$ . Film composition is controlled to be homogeneous and precisely in the very narrow range at which superconductivity occurs. Auger electron spectroscopy

reveals that the as-grown film surface is clean, without any cleaning treatment such as ion bombardment. Neither carbon nor other contaminants are seen in the spectrum. The films are single-crystal throughout and atomically flat. Specific crystal orientations of the YBCO on the substrate can be grown. Superconducting transition temperature is 90.2 K and the transition width is 1.7 K. Critical current density is  $4 \times 10^6$  A/cm<sup>2</sup> at 77 K in zero field. A.C. Meissner measurements indicate a bulk nature. These are impressive results.

Since the Sapporo conference there have been other journal reports of MOCVD deposition of high  $T_c$  films (Ref 64). These articles contain up-to-date references.

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## REFERENCES

1. J.L. Merz, "The Optoelectronics Joint Research Laboratory: Light shed on cooperative research in Japan," *Scientific Bulletin* 11(4), 1 (1986).
2. L. Esaki, Chapter 1 in *Molecular Beam Epitaxy and Heterostructures*, edited by L.L. Chang and K. Ploog (Martinus Nijhoff, Dordrecht, 1985).
3. G. Bauer, F. Kuchar, and H. Heinrich, editors, *Two-Dimensional Systems, Heterostructures, and Superlattices* (Springer-Verlag, Berlin, 1984).
4. W.T. Tsang, editor, *Semiconductors and Semimetals* 22A (Academic Press, Orlando, 1988).
5. R.B. Schoolar and J.N. Zemel, *J. Appl. Phys.* 35, 1848 (1964); J.N. Zemel, J.D. Jensen, and R.B. Schoolar, *Phys. Rev.* 140A, 330 (1965).
6. K.G. Gunther, *Z. Naturforsch.* 13a, 1081 (1968).
7. J.E. Davey and T. Pankey, *J. Appl. Phys.* 39, 1941 (1968).
8. J.R. Arthur, *J. Appl. Phys.* 39, 4032 (1968); J.R. Arthur and J.J. LePore, *J. Vac. Sci. Technol.* 6, 545 (1969).
9. L. Esaki and R. Tsu, IBM Research Note RC-2418 (1969); *IBM J. Res. Develop.* 14, 61 (1970).
10. J.P. DuChemin, S. Hersee, M. Razeghi, and M.A. Poisson, Chapter 18 in *Molecular Beam Epitaxy and Heterostructures*, edited by L.L. Chang and K. Ploog (Martinus Nijhoff, Dordrecht, 1985), pp. 678-719.
11. W.T. Tsang, *J. Cryst. Growth* 81, 261 (1987); *Appl. Phys. Lett.* 45, 1234 (1984).
12. L. Esaki, "Long journey into tunneling", in *Nobel Lectures* (in English) (Elsevier Publishing Co., Amsterdam, 1974); *Science* 183, 1149 (1974).
13. G.B. Wright, "The Fourth International Workshop on Future Electron Devices - Superlattice devices," *Scientific Bulletin* 12(1), 4 (1987).

14. E.T. Yu and T.C. McGill, *Appl. Phys. Lett.* **53**, 60 (1988); M. Tsuchiya, T. Matsusue, and H. Sakaki, *Phys. Rev. Lett.* **59**, 2356 (1987) provide a lovely demonstration of the tunneling lifetime of electrons generated in a GaAs DBQW by a picosecond laser pulse. Tunneling lifetime is found to depend upon barrier thickness in agreement with theory.
15. L. Esaki and R. Tsu, *IBM J. Res. Dev.* **14**, 61 (1970); P.A. Lebowitz and R. Tsu, *J. Appl. Phys.* **41**, 2664 (1970); R. Tsu and L. Esaki, *Appl. Phys. Lett.* **19**, 246 (1971); R. Tsu and L. Esaki, *Appl. Phys. Lett.* **22**, 562 (1973).
16. P. England, J.R. Hayes, J.P. Harbison, D.M. Hwang, and L.T. Florez, *Appl. Phys. Lett.* **53**, 391 (1988).
17. G.B. Wright, "The Tenth IEEE International Semiconductor Laser Conference," *Scientific Bulletin* **11**(4), 91 (1986).
18. A.Y. Cho, *MBE-V Sapporo Conference Workbook*, p. 1; J.S. Smith, L.C. Chiu, S. Margalit, A. Yariv, and A.Y. Cho, *J. Vac. Sci. Technol.* **B1**(2), 376 (1983); B.F. Levine, R.J. Malik, J. Walker, K.K. Choi, C.G. Bethea, D.A. Kleinman, and J.M. Vandenberg, *Appl. Phys. Lett.* **50**, 273 (1987); B.F. Levine, A.Y. Cho, J. Walker, R.J. Malik, D.A. Kleinman, and D.L. Sivco, *Appl. Phys. Lett.* **52**, 1481 (1988); B.F. Levine, C.G. Bethea, G. Hasnain, J. Walker, and R.J. Malik, *Device Research Conf.*, Boulder, CO, 20-22 June 1988 (p. II B-6).
19. A. Madhukar, *J. Vac. Sci. Technol.* **20**, 149 (1982).
20. D. Bimberg and J. Christen, "Advantages of multiple quantum wells with abrupt interfaces for light-emitting devices," in *Two-Dimensional Systems, Heterostructures, and Superlattices*, edited by G. Bauer, F. Kuchar, and H. Heinrich (Springer-Verlag, Berlin, 1984), pp. 136-146.
21. U. Gnatzmann and K. Clausecker, *Appl. Phys.* **3**, 9 (1974).
22. Y. Horikoshi and M. Kawashima, *MBE-V Sapporo Conference Workbook*, p. 25; *Jpn. J. Appl. Phys.* **25**, L868 (1986); F. Briones, L. Gonzales, M. Recio, and M. Vazquez, *Jpn. J. Appl. Phys.* **26**, L1125 (1987); Y. Horikoshi, M. Kawashima, and H. Yamaguchi, *Jpn. J. Appl. Phys.* **27**, 169 (1988).
23. S. Koshiba, S. Nanao, O. Tsuda, Y. Watanabe, Y. Sakurai, H. Sasaki, H. Kawata, and M. Ando, *MBE-V Sapporo Conference Workbook*, p. 57; *Proc. of JIMIS-5: Non-Equilibrium Solid Phases of Metals and Alloys* (Japan Institute of Metals, Sendai, Japan, 1988), p. 403.
24. H. Sakaki, M. Tanaka, and J. Yoshino, *Jpn. J. Appl. Phys.* **24**, L417 (1985); M. Tanaka and H. Sakaki, *J. Cryst. Growth* **81**, 153 (1987); C.W. Tu, R.C. Miller, P.M. Petroff, T.D. Harris, R.F. Kopf, S.K. Sputz, and M.G. Lamont, *J. Cryst. Growth* **81**, 159 (1987).

25. W.T. Tsang, *MBE-V Sapporo Conference Workbook*, p. 161.
26. Y. Aoyagi, A. Doi, S. Iwai, and S. Namba, *J. Vac. Sci. Technol.* B5, 1460 (1987); J. Nishizawa, H. Abe, and T. Kurabayashi, *J. Electrochem. Soc.* 132, 1197 (1985); N.H. Karam, L.I. Yoshida, and S.M. Bedair, *Appl. Phys. Lett.* 52, 1144 (1988).
27. K. Nagata, Y. Iimura, Y. Aoyagi, S. Namba, and S. Den, *MBE-V Sapporo Conference Workbook*, p. 177.
28. K. Kondo, *MBE-V Sapporo Conference Workbook*, p. 226.
29. H. Kukimoto, *MBE-V Sapporo Conference Workbook*, p. 518.
30. N. Bottka and D.K. Gaskill, "The Fourth International Conference on Metal-Organic Vapor Phase Epitaxy," *Scientific Information Bulletin* 13(3), 31 (1988).
31. G.C. Osbourn, *Phys. Rev.* B27, 5126 (1983).
32. K. Miki, K. Sakamoto, T. Sakamoto, H. Okumura, N. Takahashi, and S. Yoshida, *MBE-V Sapporo Conference Workbook*, p. 90; K. Sakamoto, T. Sakamoto, S. Nagao, G. Hashiguchi, K. Kuniyoshi, and Y. Bando, *Jpn. J. Appl. Phys.* 26, 666 (1987); T. Sakamoto and G. Hashiguchi, *Jpn. J. Appl. Phys.* 25, L78 (1986).
33. J. Bevk, J.P. Mannaerts, L.C. Feldman, B.A. Davidson, and A. Ourmazd, *Appl. Phys. Lett.* 49, 286 (1986).
34. G. Abstreiter, K. Eberl, E. Friess, W. Wegscheider, and R. Zachai, *MBE-V Conf. Proc.* (to appear); E. Kasper, H. Kibbel, H. Jorke, H. Brugger, E. Friess, and G. Abstreiter, *Phys. Rev. B* (15 August 1988); K. Eberl, W. Wegscheider, E. Friess, and G. Abstreiter, "Heterostructures on Si: One step further with Si," in *Cargese Workshop, NATO ASI Series*, edited by Y.T. Nissim (1988); R. Zachai, E. Friess, G. Abstreiter, E. Kasper, and H. Kibbel, *Proc. 19th Int. Conf. on Physics of Semiconductors*, Warsaw, Poland, 15-19 August 1988.
35. S.J. Chang, C.F. Huang, M.A. Kallel, K.L. Wang, R.C. Bowman, Jr., and P.M. Adams, *MBE-V Sapporo Conference Workbook*, p. 98.
36. K. Sawada, M. Ishida, T. Nakamura, and T. Suzuki, *MBE-V Sapporo Conference Workbook*, p. 257; M. Ishida, I. Katakabe, N. Ohtake, and T. Nakamura, *Appl. Phys. Lett.* 52, 1326 (1988); K. Sawada, M. Ishida, N. Ohtake, and T. Nakamura, *Appl. Phys. Lett.* 52, 1672 (1988).
37. W. Stolz, Y. Horikoshi, M. Naganuma, and K. Nozawa, *MBE-V Sapporo Conference Workbook*, p. 129; W. Stolz, M. Naganuma, and Y. Horikoshi, *Jpn. J. Appl. Phys.* 27, L283 (1988).
38. H. Kroemer, T.-Y. Liu, and P.M. Petroff, *MBE-V Sapporo Conference Workbook*, p. 138.
39. G.B. Wright, "Growth of low resistivity II-VI crystals at the Tokyo Institute of Technology," *Scientific Information Bulletin* 13(2), 1 (1988).

40. R.L. Gunshor, L.A. Kolodziejski, M.R. Melloch, M. Vaziri, C. Choi, and N. Otsuka, *Appl. Phys. Lett.* **50**, 200 (1987); M.C. Tamargo, J.L. deMiguel, D.M. Hwang, and H.H. Farrell, *J. Vac. Sci. Technol.* **B6**, 784 (1988); G.D. Studtmann, R.L. Gunshor, L.A. Kolodziejski, M.R. Melloch, J.A. Cooper, Jr., R.F. Pierret, and D.P. Munich, *Appl. Phys. Lett.* **52**, 1249 (1988).
41. R.D. Feldman, M. Oron, R.F. Austin, and R.L. Opila, *J. Appl. Phys.* **63**, 2872 (1988).
42. M.D. Lange, S. Sivananthem, X. Chu, and I.P. Faurie, *Appl. Phys. Lett.* **52**, 978 (1988).
43. M. Kitagawa, Y. Tomomura, A. Suzuki, and S. Nakajima, *MBE-V Sapporo Conference Workbook*, p. 270.
44. H. Cheng, J.M. DePuydt, J.E. Potts, and M.A. Haase, *MBE-V Sapporo Conference Workbook*, p. 274.
45. K. Ohkawa, T. Mitsuyu, and O. Yamazaki, *Extended Abstracts of the 18th (1986 International) Conference on Solid State Devices and Materials*, Tokyo, 1986, pp. 635-38.
46. J.D. Benson, D. Rajavel, B.K. Wagner, R. Benz, II, and C.J. Summers, *MBE-V Sapporo Conference Workbook*, p. 302.
47. M. Voos, *MBE-V Sapporo Conference Workbook*, p. 354; J. Bleuse, G. Bastard, and P. Voisin, *Phys. Rev. Lett.* **60**, 220 (1988) and references therein; E.E. Mendez, F. Agullo-Rueda, and J.M. Hong, *Phys. Rev. Lett.* **60**, 2426 (1988).
48. A.C. Gossard, J.H. English, M. Miller, and R.J. Simes, *MBE-V Sapporo Conference Workbook*, p. 334.
49. M. Shayegan, V.J. Goldman, T. Sajoto, M. Santos, C. Jiang, and H. Ito, *MBE-V Sapporo Conference Workbook*, p. 338.
50. J.E. Cunningham, G. Timp, A.M. Chang, T.H. Chiu, W. Jan, E.F. Schubert, and W.T. Tsang, *MBE-V Sapporo Conference Workbook*, p. 342.
51. K. von Klitzing, G. Dorda, and M. Pepper, *Phys. Rev. Lett.* **45**, 494 (1980).
52. T. Ando and Y. Uemura, *J. Phys. Soc. Jpn.* **36**, 959 (1974).
53. D.C. Tsui, H.L. Stormer, and A.C. Gossard, *Phys. Rev. Lett.* **48**, 1559 (1982).
54. R.B. Laughlin, *Phys. Rev. Lett.* **50**, 1395 (1983).
55. A.B. Fowler, F.F. Fang, W.E. Howard, and P.J. Stiles, *Phys. Rev. Lett.* **16**, 901 (1966).
56. P.M. Petroff, J. Gaines, M. Tsuchiya, R. Simes, L. Coldren, H. Kroemer, J. English, and A.C. Gossard, *MBE-V Sapporo Conference Workbook*, p. 382.
57. K.Y. Lee, J.M. Hong, T.P. Smith, III, C.M. Knoedler, S.E. Laux, and D.P. Kern, *MBE-V Sapporo Conference Workbook*, p. 389.
58. P.R. Pukite, G.S. Petrich, and P.I. Cohen, *MBE-V Sapporo Conference Workbook*, p. 390.

59. K. Kanamoto, K. Fujiwara, Y. Tokuda, N. Tsukada, M. Ishii, and T. Nakayama, *MBE-V Sapporo Conference Workbook*, p. 391.

60. P.M. Petroff, A.C. Gossard, and W. Wiegmann, *Appl. Phys. Lett.* **45**, 620 (1984).

61. J.M. Gaines, P.M. Petroff, H. Kroemer, R.J. Simes, R.S. Geels, and J.H. English, *J. Vac. Sci. Technol.* **B6**(4), 1378 (1988).

62. T. Terashima, K. Iijima, K. Yamamoto, J. Takada, K. Hirata, H. Mazaki, and Y. Bando, *MBE-V Sapporo Conference Workbook*, p. 510; T. Terashima et al., *Jpn. J. Appl. Phys.* **27**, L91 (1988).

63. M. Osofsky, P.R. Broussard, and E. Callen, "High temperature superconducting films in Japan," *Scientific Information Bulletin* **13**(4), 1 (1988).

64. J. Zhao, K.-H. Dahmen, H.O. Marcy, L.M. Tonge, T.J. Marks, B.W. Wessels, and C.R. Kannewurf, *Appl. Phys. Lett.* **53**, 1750 (1988); A.J. Panson, R.G. Charles, D.N. Schmidt, J.R. Szedon, G.J. Machiko, and A.I. Braginski, *Appl. Phys. Lett.* **53**, 1756 (1988).

Kiyoshi Takahashi was chairman of the Organizing Committee of the Fifth International Conference on Molecular Beam Epitaxy, the subject of this report. He is a professor in the Department of Electrical and Electronic Engineering of the Tokyo Institute of Technology. Professor Takahashi has held visiting appointments at the Carnegie-Mellon University in Pittsburgh, the National Polytechnic Institute in Mexico City, and the University of Sao Paulo in Brazil. Besides MBE, heterojunctions, and semiconductor materials, his current research interests include solar cells and various kinds of sensors.

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# THE 10TH INTERNATIONAL CONGRESS ON RHEOLOGY

Bruce Hartmann

**P**apers presented at the 10th International Congress on Rheology covered a broad range of topics. This article focuses on those papers dealing with polymer physics.

The Tenth International Congress on Rheology was held in Sydney, Australia, from 14 to 19 August 1988. About 300 delegates from 32 countries attended. The largest contingent was from the host country, Australia, with 77. The United States followed with 68 attendees. The United Kingdom and West Germany had 23 each, while Japan and France each sent 13 representatives. The Congress Organizer, Roger Tanner (University of Sydney), was pleased to note that there were 9 attendees from the People's Republic of China. In contrast, the two delegates scheduled from the U.S.S.R. did not show up.

Some 260 papers were presented in 14 categories: General Theory, Polymer Solutions, Suspensions, Polymer Processing, Numerical Methods, Fluid Mechanics, Polymer Blends, Rheometry, Polymer Melts, Composites and Solids, Blood Rheology, Biorheology, Industrial Rheology, and Liquid Crystals. Presentations from academic institutions made up 80 percent of the total. The two-volume Proceedings contain three-page extended abstracts of the presentations.

Some of the papers that I found most interesting (reflecting my specialty in polymer physics) are as follows. R. Byron Bird (University of Wisconsin) gave the Plenary lecture, in which he discussed the influence of J.G. Oldroyd and J.G. Kirkwood on rheology. The former was principally interested in continuum mechanics and the latter in statistical mechanics. D.G. LeGrand (General Electric) discussed the thermal stresses and resulting crack propagation found in the extrusion and injection molding of thermoplastics. Though seemingly not a very elaborate model, a typical computer run takes 30 minutes on a Cray. T.G.M. Van de Ven (McGill University) presented an invited paper on the combined effects of shear and electrical field on dilute suspensions of nonspherical particles. A negative complex viscosity can be obtained as a result of pumping electrical energy into the system. In J.M. Caruthers' (Purdue University) paper he defined a new time scale based not on the hole fraction of the Simha-Somcynsky equation of state but on the entropy, as suggested by Adam and Gibbs. Good agreement with data for poly(vinyl acetate) and an epoxy was shown. A.B. Metzner (University of Delaware) presented an invited paper on the processing behavior of glass fiber filled polypropylene going up to high concentration (40 percent by weight or 20 percent by volume). The fibers tend to cluster, and the



viscosity varies considerably with the clustering. D.J. Plazek (University of Pittsburgh) presented some data for simultaneous shearing and orthogonal oscillation. The results could not be interpreted using theories for the entanglement molecular weight and were left as a puzzle. T.S. Chow (Xerox) presented results on time-temperature superposition in the glassy state based on his hole theory. Good agreement with dynamic mechanical data, using only one adjustable parameter, was obtained. R. Simha (Case Western Reserve University) discussed physical aging in which an o-positronium probe was used to determine the free volume distribution as a function of time at various temperatures. D.J. Evans (Australian National University) presented an invited paper on molecular dynamics simulations in which he discussed ways of optimizing the computer algorithms. His major achievement has been to study a molecule as large as decane, but he is a long way from polymers. D.-C. Wu (Chengdu University of Science and Technology) described the use of atactic polypropylene coated fillers (such as calcium carbonate) in a polypropylene matrix, for example. The fillers are used to lower the cost and the coating gives better processing characteristics. D. Mewes (Universitat Hanover, FRG) presented a

paper related to the use of a gas dissolved in oil to lower the viscosity, enabling the oil to be recovered from the ground more easily. Specifically, the paper concerned an instrument for measuring viscosity up to a pressure of 8 kbar.

The International Rheology Committee accepted the offer from Brussels to host the next Congress, in 1992. Although they were not chosen, it is a sign of the emergence of China into the mainstream of international science that they also offered to host the next Congress.

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# NEW DIAMOND SCIENCE AND TECHNOLOGY

F.S. Pettit

"Your diamonds are not in far distant mountains, or in yonder seas; they are in your own backyard if you but dig for them"  
(Russell Conwell, founder of Temple University).

**T**he First International Conference on the New Diamond Science and Technology is used to assess the current status of diamond science and technology in Japan. The 106 papers and poster papers that were presented at this conference are briefly described. The current status of the diamond science and technology is then discussed by considering: the theory for diamond film formation, structures of diamond films, processing conditions for the fabrication of diamond films, applications for diamond and diamondlike films, synthetic diamond crystals, and cubic boron nitride. The Japanese effort on diamond technology is shown to be substantial and impressive. The emphasis is on applications as opposed to theory and mechanistic models. The first applications of diamond films will use properties such as hardness and thermal conductivity. The current technology appears to be adequate to use such films on a limited number of cutting tool substrates. Other applications for diamond films, as well as cubic boron nitride films, will be forthcoming.

## INTRODUCTION

Diamond possesses many attractive properties. It is extremely hard and has the highest thermal conductivity at room temperature of any known material. It has good

optical transparency over a range of wavelengths. Its density is low. It is nontoxic and does not react with most environments at temperatures below about 400 °C. Finally, it becomes a n- or p-type semiconductor when doped with appropriate impurities. Beyond any doubt, diamond will be used in a great variety of technical applications when it can be fabricated reproducibly with controlled properties at reasonable costs.

Diamond for industrial applications is made by two types of processes, one conducted at high pressures and the other at much lower pressures. An important difference between these two processes is that the high pressure synthesis is under conditions in which diamond is the stable phase, whereas the other uses conditions under which diamond is metastable.

Synthetic diamond up to about a few millimeters in size can be grown from liquid metals or alloys of such metals as iron, cobalt, or nickel at high pressures by imposing a temperature gradient. Diamond is formed from graphite due to the solubility differences of carbon and diamond in the liquid under the imposed temperatures and pressure. Large diamonds of over 11 carats are best grown by using a reconstitution technique where diamond is the source of carbon. Such techniques are versions of that developed by the General Electric Company over 20 years ago (Ref 1 and 2). This method is appropriate for growing

individual diamond crystals and orientation can be controlled by using diamond seed crystals.

The other method consists of forming diamond films by using various chemical vapor deposition (CVD) techniques. The ability to deposit diamond films using vapor deposition was first demonstrated by Derjaguin and coworkers (Ref 3 and 4) and subsequently by Matsumoto, Sato, Kamo, and Setaka (Ref 5 and 6). It is now certain that diamond can be synthesized by the thermal decomposition of a number of organic compounds on heated substrates. The chemical mechanism for diamond deposition via CVD is not fully understood. Typical deposition conditions consist of a reactant mixture of methane in hydrogen (0.1 to 2.0 percent methane, 20 to 30 Torr total pressure, 100 SCCM total flow) with a heated tungsten filament (1,600 to 2,400 °C) suspended 3 to 22 mm above the temperature-controlled substrate upon which diamond is to be formed. A number of substrates have been used, including silicon, tantalum, quartz glass, and some carbides, the principal characteristic being that conditions are developed whereby carbon does not dissolve into them.

To grow metastable diamond films by the CVD method the deposition of stable graphitic or amorphous carbon must be prevented. The situation is similar to the formation of metastable phases during the age hardening of certain metallic alloys. In such cases the metastable phase forms since the free energy fluctuation required to nucleate it is less than that for the stable phase. In diamond film growth from

organic vapors, diamond and graphite formation both lower the free energy of the system, but diamond can be formed if it can be nucleated faster than graphite. Of course, nucleation of graphite in the deposited diamond must also be prevented.

As a result of the potential for diamond to be used in numerous technical applications, and the high probability that processes eventually will be developed to produce diamond in various forms, the Japan New Diamond Forum (JNDF) was established in 1985. JNDF is a nonprofit body to promote basic research, industrial application, and information exchange of man-made diamond. Since its inception, JNDF has had a number of lecture meetings, symposia, and open seminars. The lecture meetings are restricted to members of JNDF, but the symposia and seminars are open to all. JNDF publishes a journal, quarterly in 1987, and an annual English edition was recently published. The first and second diamond symposia were held in Tokyo in November 1986 and December 1987, respectively. The First International Conference on the New Diamond Science and Technology was held in Tokyo on 24-26 October 1988. In this article the papers presented at the First International Conference will be discussed and then certain issues important to the diamond technology, namely, the current status of the science and technology for diamond films, synthetic crystals, as well as cubic boron nitride, and advances necessary for effective utilization of this technology, will be examined.

## **THE FIRST INTERNATIONAL CONFERENCE ON THE NEW DIAMOND SCIENCE AND TECHNOLOGY**

The First International Conference on the New Diamond Science and Technology had 390 participants from 18 countries with 90 participants from overseas. Including poster papers, 106 papers were presented. The proceedings from this meeting are planned for publication at the end of March 1989. In the following most of the papers are discussed by considering the major themes of this conference.

### **Gaseous Phase Deposition**

Spitsyn (P1-01)\* reviewed the early developments for diamond film growth and emphasized the importance of highly active hydrocarbon molecules and radicals in increasing diamond growth rates. In the activated gaseous media the continuous generation of atomic hydrogen was proposed to be necessary in order to prevent graphite formation along with diamond. Different types of activation of gaseous media, such as thermal, microwave discharge, and lasers, were discussed as methods for forming diamond films. Spitsyn also discussed doping diamond films with boron to make a p-type semiconductor and with phosphorous to make an n-type semiconductor. An attempt was made to make a pn junction but it evidently was not successful.

Messier et al. (P1-02) reviewed work being performed at Penn State and also discussed some of the fundamental issues concerning diamond film growth that included identification of dominant gas phase species (Ref 7), transmission electron microscopy (TEM) identification of lattice defects (Ref 8) and graphite inclusions (Ref 9), and the effects of oxygen (Ref 10) and metal impurities (Ref 11) on nucleation density and film growth rates.

Angus and Schmidt (P1-03) discussed the importance of hydrogen in stabilizing diamondlike hydrocarbons and postulated likely diamond precursors based upon crystal growth considerations. Butler et al. (P1-04) emphasized the importance of determining the chemical species necessary for diamond formation and suggested the role of the hot filament is primarily to heat the gas.

Tamou (P1-05) characterized diamond films formed in a conventional hot filament CVD apparatus by using scanning electron microscopy (SEM), x-ray diffraction (XRD), Raman spectroscopy, and TEM. These films were polycrystalline diamond. No other phase was detected at the boundaries between grains; however, at low substrate temperatures lamellar, pyrolytic carbon was observed on the surfaces of the films. The diffraction patterns of individual grains showed multiple-twinning with nonperfect fivefold symmetry as has been reported and discussed in previous conferences. Ravi et al. (P1-06) showed

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\*Titles, authors, and organizations are given in Appendix A.

mesh-supported films (2 cm in diameter) formed via CVD that were diamond or diamondlike covering large areas appropriate for commercial products.

A number of papers were concerned with procedures and techniques to deposit diamond and diamondlike films. Ueno and Wasa (P1-08) used an electron bombardment ion source with a graphite target to deposit diamond and diamondlike films on a silicon single crystal at room temperature with growth rates of 300 to 400 nm/h. Sputtering conditions were: target-graphite plate, 10 cm in diameter; ion source energy, 1,200 eV; ion source current, 60 mA; ion source beam aperture, 25 mm in diameter; gas pressure,  $5 \times 10^{-5}$  to  $2 \times 10^{-4}$  Torr; target-ion source spacing, 250 mm. Hirose (P1-09) used a combustion flame to deposit diamond at atmospheric pressure and growth rates of 100 to 150  $\mu\text{m}/\text{h}$ . The specimen to be coated was supported on a water-cooled holder and positioned within the inner flame of the torch. The gases used consisted of oxygen and hydrocarbons such as acetylene, ethylene, propane, and methane. Typical synthesis conditions were: atmosphere, in air; gas pressure, 1 atm; reactant gases,  $\text{C}_2\text{H}_2 + \text{O}_2$  and  $\text{C}_2\text{H}_2 - 1$  to 5 L/min,  $\text{O}_2 - 1$  to 5 L/min,  $\text{O}_2/\text{C}_2\text{H}_2 \leq 1$ ; substrate temperature, 600 to 1,100  $^\circ\text{C}$ ; substrates, Si and WC-Co. Kamada et al. (P1-10) used dc discharge (1 kV and 3.5 A/cm<sup>2</sup>) plasma chemical vapor deposition (2 vol % of  $\text{CH}_4$  in  $\text{H}_2$  at 200 Torr and flow rate of 400 SCCM) to form uniform, polycrystalline diamond films 120  $\mu\text{m}$  thick on a mirror-polished Si(111) substrate at 800 to 900  $^\circ\text{C}$ . These films, formed in a 16-hour period, appeared to be diamond and were composed of columnar grains with a (110) texture.

Kawarada et al. (P1-11) used a similar apparatus to form a film 2 mm thick over an area of 100 mm<sup>2</sup> and substantiated that the diamond film performed well as a heat sink. This synthesized diamond film had a density of 3.4 g/cm<sup>3</sup>, a resistivity of  $10^4$  to  $10^5 \Omega\text{-cm}$ , a thermal conductivity of 800 W/m-K, and a Vickers hardness of 10,000 kg/mm<sup>2</sup>. Mitsuda et al. (P1-12) used a microwave plasma jet torch to deposit diamond films at 30  $\mu\text{m}/\text{h}$  and the growth rate increased with the concentration of  $\text{CH}_4$ . Typical experimental conditions were: gas flow rates,  $\text{H}_2 - 20$  L/min, Ar - 5 to 30 L/min,  $\text{CH}_4 - 0.2$  to 2 L/min; total pressure, 0.1 MPa; microwave power, 2 to 5 kW; substrate material, Si(100); substrate surface area,  $\sim 6$  cm<sup>2</sup>; substrate temperature, 1,000 to 1,600 K; electrode gap, 10 mm. Tanabe et al. (P1-13) formed diamond films with good crystallinity by using microwave plasma CVD in which the feed gas was  $\text{CH}_4$  and  $\text{O}_2$ . Typical experimental conditions were: microwave power, 450 W; frequency, 2.45 GHz; total gas flow, 300 SCCM; feed gases,  $\text{O}_2$  and  $\text{CH}_4$  with  $\text{CH}_4/\text{O}_2$  ratios from 0.5 to 3; pressure, 10.6 and 17.3 kPa; substrate temperature, 900  $^\circ\text{C}$ ; substrate, Si(100); surface area,  $\sim 4$  cm<sup>2</sup>. The growth rates increased from 2 to 3  $\mu\text{m}/\text{h}$  at 10.6 kPa to 6 to 8  $\mu\text{m}/\text{h}$  at 17.3 kPa and optimum crystallinity was obtained with a  $\text{CH}_4/\text{O}_2$  ratio of 1.5. Such results indicate hydrogen may not always be necessary at high concentrations in order to have diamond film formation.

Badzian and Badzian (P1-14) discussed the crystallization of diamond from hydrocarbon and hydrogen plasmas and showed graphite nucleation introduces defects in diamond single crystals and polycrystalline films. Sato et al. (P1-15)

described studies concerned with the structure of diamond films. These films were made using microwave plasma CVD with 3 and 4 percent methane at a total pressure of 40 Torr. The films were then subjected to plasma etching using air or oxygen. This etching resulted in preferential attack of the films at grain boundaries with long columnar grains remaining. Electron diffraction showed that each of these grains were single crystals containing stacking faults. These grains were 0.5 to 3  $\mu\text{m}$  in diameter and about 30  $\mu\text{m}$  in length. They were thinner at the bottom near the substrate. These shapes must develop as the plasma etch removes the graphitic and amorphous carbon phases from the films.

### **Electric and Thermal Properties and Functional Applications**

Several papers were concerned with the influence of impurities on defects in synthetic diamonds as evidenced by optical absorption and cathodoluminescence techniques. Such films were successfully used as an antireflection coating on Si and Ge, and thermal conductivity measurements showed their usefulness as heat transfer media. Yazu (P2-02) reported a new defect due to nitrogen that showed a zero-phonon line at 987 nm in absorption and emission spectra. Kawarada et al. (P2-07) observed increased visible cathodoluminescence of boron-doped diamond films formed by using microwave CVD.

Shohata et al. (P2-05) investigated the mechanical properties of diamondlike films deposited in a dc-glow discharge plasma of methane and hydrogen. Young's moduli for these films were about 70 percent of the diamond crystal value and did vary with the methane/hydrogen ratio.

Contact-stylus tests (head weight of 15 grams) on 3.5-inch-diameter hard disks for a magnetic drive application were run at speeds of 4.4 m/s (1,000 rpm). No wear trace was evident after 100,000 revolutions. It was concluded that it was possible to deposit thin (near 200 Å) films that are wear resistant.

Among the papers concerned with functional applications was that of Nakahata et al. (P2-06), who made thermistors using undoped and boron-doped diamond films and characterized their properties. In the case of the boron-doped diamond films deposited on a surface 5.7 mm<sup>2</sup> and 1 to 2  $\mu\text{m}$  thick, resistances of  $10^4$  to  $10^2$  ohms were obtained at room temperature and 600 °C, respectively, compared to  $10^{10}$  to  $10^6$  ohms for an undoped diamond thermistor. Yalamanchi et al. (P2-04) reported on diamondlike carbon films for infrared (IR) optical devices. Collins (P2-01) used these techniques to describe the effects of nitrogen and nitrogen getters in synthetic diamonds. Kumashiro et al. (P2-03) reported on the thermal properties of single-crystal boron phosphide made by the CVD process. It was found that boron phosphide had a Debye temperature of 1,000 °C and was a promising material for heat sinks.

### **High Pressure Synthesis**

Mishima et al. (P2-08) used the temperature gradient method to grow single crystals of cubic boron nitride (cBN). Crystals of about 3 mm in size were obtained by appropriate selection of conditions. A pn junction diode was fabricated by growing a silicon-doped n-type crystal epitaxially on a beryllium-doped p-type seed crystal. The rectification characteristics

were observed from room temperature to 650°C, and this diode was also functional as a light-emitting diode. When questioned about growing diamond on cBN, it was stated that it is to be a future project. Fukunaga (P2-10) reported that while growth of cBN single crystals is more difficult than diamond, this results from lack of knowledge of proper solvents and the optimum conditions for growing crystals. More data on these variables are required and then high growth rates for industrial production at pressures of 3.5 to 4 GPa should be possible.

Cubic boron nitride (P2-16) was fabricated by using the temperature gradient method and  $\text{Li}_3\text{BN}_2$  as solvent. Crystals up to 2.6 mm were grown consistently on a seed without spontaneous nucleation. Cubic boron nitride (98-percent dense) was also fabricated (P2-14) by reaction sintering while simultaneously transforming hBN to cBN under high pressure and adding cBN seed crystals.

A few papers were concerned with consolidation of diamond powders. Sawaoka and Akashi (P2-11) investigated dynamic compacting of diamond powders under shock compression conditions. Well-bonded diamond compacts were obtained from 2- to 4- $\mu\text{m}$  and 10- to 20- $\mu\text{m}$  diamond powders at a pressure of 90 GPa. It was reported that by including reactive powders with the passive powders the compaction process was more effective. For example, when silicon was mixed with diamond powder, improved compacts were obtained with diamond particles bonded by SiC. Cubic boron nitride was also made by this technique with hardnesses up to 80 GPa. However, microhardness measurements gave variable readings throughout these compacts due to pressure and temperature

variations during fabrication. Optimization remains to be accomplished. Uehara and Yamaya (P2-13) sintered diamond powders with different particle sizes at a pressure of 6 GPa and 1,823 K by using a cobalt infiltration process. Cobalt content in the compacts decreased with increasing particle size whereas Knoop hardness increased with increasing particle size. Burris (P2-12) described preparation of good quality diamond, up to 11 carats in weight, via a reconstitution technique using diamond as a source by the temperature gradient method. Applications for such diamonds were described and included cutting tools, thermoluminescent dosimeters, and radiation detectors.

Novikov (P2-15) discussed processes for growing diamond crystals at rates of 4 mm/h, the highest rates reported at this meeting, from a magnesium carbide melt containing other unspecified ingredients in the temperature gradient method. The effect of absorbed hydrogen on carbon used for growing diamond (P2-18) crystals was examined and it was proposed that hydrogen impeded the dissolution of carbon into the catalyst metal rather than affecting crystallization of diamond. Finally, Niedbalska et al. (P2-19) proposed that the pressure to grow diamond may be lowered by using feedstocks such as schungite, an amorphous carbon available naturally in Russia, or natural glassy carbon rather than crystalline graphite.

### **Machining and Mechanical Properties**

Brookes et al. (P-Invited) discussed the mechanical properties of the various types of diamond and showed that the behavior of diamond was typical of that for cubic materials having high stacking fault

energies. Infrared absorption can be used to differentiate between type I and type II diamond. In type I the nitrogen concentration is sufficient to be detected by infrared absorption; further subdivisions (Ia, Ib) can be made by considering the shapes of the absorption spectra, which indicate the particular distribution of the nitrogen. Type II diamonds contain lower levels of impurities and have smoother absorption spectra. They are rare in nature.

Wapler (P3-01) discussed various applications for diamond and cubic boron nitride, which included saw blades, wire-drawing dies, grinding wheels, drill bits, and single-crystal turning tools, and proposed with confidence increased utilization including new areas of application. Bovenkerk (P3-02) discussed the reactivity and wear of diamond and cBN. The principal processes that caused degradation were identified as attrition, oxidation, graphitization, gross fracture, thermal cracking, and chemical reaction. When selecting between diamond and cBN for various applications, the importance of considering the differences between their reactivities was stressed.

A number of papers were concerned with properties of diamond tools. Shimada et al. (P3-03) showed that the lives of diamond cutting tools were affected by defect densities. At temperatures above about 800 K, strengths deteriorate and this deterioration is accelerated in the presence of iron. These observed effects were suggested to occur due to elongation of surface cracks via oxidation. Asai et al. (P3-04) described a new scanning electron microscope with two secondary electron detectors to measure the cutting edge radius of diamond tools to 20 to 60 nm for ground

tools and to about 10 nm with ion-sputter-etched diamond tools. Nishimura et al. (P3-05) described methods to control the corner radii of diamond tools to 10 nm precision and obtain a sharp cutting edge producing 1-nm-thick chips.

Diamond films formed on WC-Co cemented carbide by microwave plasma CVD were compared as a function of surface condition of the carbide and for two levels of methane concentrations (P3-07). The films formed in 1-percent  $\text{CH}_4$  were shown to reduce tool flank wear most effectively, and the adhesive strength was dependent on substrate surface condition. Sung (P3-08) showed the bonding of diamond bodies to tools could be improved by using refractory metal coatings.

### Physical and Chemical Properties and Geoscience

Glass et al. (P3-10) used transmission electron microscopy to characterize thin diamond films grown by microwave-plasma-enhanced chemical vapor deposition on n-type Si (111) substrates at 800 °C. The deposition conditions were maintained constant with only the  $\text{CH}_4/\text{H}_2$  ratio in the feed gas varied between 0.3 and 2 percent  $\text{CH}_4$  in hydrogen. The films were composed of columnar grains. The structure at the junctions of these columnar grains was not defined. Dislocations, stacking faults, and other defects were observed in the individual grains with twinning being the most predominant defect. The density of defects in films grown with 2 percent methane appeared to be significantly higher than that observed in the films grown with 0.3 percent. The film grown in the 0.3-percent  $\text{CH}_4$  contained an interfacial layer separating it



from the silicon substrate. This layer was approximately 50 Å thick and was identified as  $\beta$ -SiC, which was epitaxially orientated with the silicon substrate. Electron microscopy was also used by Mar et al. (P3-11) to characterize diamond particles formed on silicon by plasma-assisted chemical vapor deposition. These particles possessed features indicating the diamond nucleated at various sites and then grew more or less concentrically to form polyhedrons. As the  $\text{CH}_4$  concentration was increased the diamond particles exhibited more spherical shapes with the concomitant formation of an amorphous phase. Kobayashi et al. (P3-12) studied the etching characteristics of diamond and amorphous carbon films by using an rf plasma discharge system. The etching rates of amorphous carbon were three times larger than those for diamond films.

A number of papers were concerned with defects in synthetic and natural diamond crystals. Kanda et al. (P3-13) studied the formation of nitrogen pairs in synthetic diamonds grown from molten cobalt at temperatures between 1,350 and 1,500 °C under 6 GPa. Based upon analyses of infrared absorption spectra, the crystals contained both paired and single substitutional nitrogen. Moreover, the nitrogen pairs increased with growth temperatures above 1,450 °C. Sumida et al. (P3-14) used electron microscopy to observe lattice defects such as dislocations in natural diamond. Pate et al. (P3-15) studied the electronic structure of clean (110) and (111) surfaces of diamond. Bonding models for atoms on these surfaces were suggested.

Satoh (P3-16) found that in large synthetic diamond the nitrogen concentration of the (111) growth sectors differs from the (100) growth sectors and these differences depended upon temperature.

Togaya (P3-19) presented results obtained by melting diamond under high pressures that indicated that the phase diagram of carbon in terms of pressure and temperature contains some significant uncertainties.

## POSTER PAPERS

The poster papers covered a range of topics. Some of these papers will be briefly described by considering various topics related to the new diamond technology.

### Diamond Films

**Nucleation, Growth, and Morphology.** Kobashi et al. (PP2-01)\* described the surface morphologies of diamond films formed by CVD. Diamond crystals were formed on silicon wafers with various orientations that depended upon the methane concentration. The surface morphology of the films changed cyclically during film growth. Well-defined crystallographic planes were observed to appear, disappear, and reappear. Boron-doped diamond films were also synthesized by adding diborane ( $\text{B}_2\text{H}_6$ ) to the gas, and the surface morphologies of the films were affected by the boron-containing gaseous species. Hata et al. (PP2-13) studied the reactive etching of diamond films grown on

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\*Titles, authors, and organizations are given in Appendix B.

silicon by microwave-plasma-assisted vapor deposition using methane concentrations ranging from 0.3 to 5 vol %. At low methane concentrations of 0.5 percent the surface morphology consisted of well-defined crystal faces with twins. The cross sections of these films produced by fracturing suggested textured growth, but discrete crystallites could not be discerned. Etching of such cross sections resulted in pit formation at grain boundaries. At methane concentrations of 3 to 4 percent the surface morphologies of the films were characterized by (100) crystal faces that were parallel to the substrate surface. The fractured surfaces exhibited a typical columnar-grained structure that was rapidly etched to thin rods of diamond due to preferential attack of the graphitic-rich intergranular regions. The Raman spectra for these etched diamond needles were as narrow as that observed with natural diamond. The diamond film formed with 5 percent methane did not exhibit a well-defined crystalline morphology and etching produced a porous network of threadlike fibers. Yugo and Kimura (PP2-20) examined the effects of substrate surface condition on diamond film morphologies that developed during plasma CVD deposition. It was shown that the substrate surface condition affected the morphology of diamond films by influencing the number of nucleation centers.

**Synthesis of Films.** Hirabayashi et al. (PP2-03) described the selective deposition of polycrystalline diamond films and single-crystal diamond particles on silicon substrates using CVD and by controlling nucleation centers via substrate surface roughening. Polycrystalline diamond was selectively deposited, but single-crystal

diamond could not always be formed selectively. Matsumoto and Furukawa (PP2-04) attempted to form diamond films via CVD on molybdenum and titanium substrates by forming films of carbide prior to diamond deposition. Diamond was detected on both substrates, but amorphous graphite was also detected with more of this component on the titanium substrate. Wood et al. (PP2-05) attempted to deposit diamond films using plasma-enhanced CVD at temperatures between 500 and 650 °C but were unsuccessful and proposed that microwave, rf discharges, and heated filaments may raise substrate surface temperatures to appropriate levels. Suzuki et al. (PP2-06) obtained uniform diamond films by using a magneto-microwave plasma with CO and H<sub>2</sub> to enhance deposition over larger areas. Ishibori and Ohira (PP2-07) described a microwave plasma CVD apparatus that used CO added to CH<sub>4</sub> and H<sub>2</sub> gases in which uniform diamond films about 5 μm thick were formed after 16 hours on substrates about 100 cm square. Kamo et al. (PP2-09) investigated the enlargement of the microwave region and the diamond deposition area. A method of introducing microwaves from two directions was found to be suitable for diamond deposition on substrates as large as 1 cm in diameter. Toshima et al. (PP2-10) demonstrated that diamond films could be deposited on silicon wafers using CH<sub>4</sub>(1 vol %)-H<sub>2</sub>, (CH<sub>3</sub>)<sub>2</sub>CO(1 vol %)-H<sub>2</sub>, and CO(10 vol %)-H<sub>2</sub> plasmas generated by microwave discharge and proposed CH<sub>3</sub> radicals as an important species for diamond film formation. Snail et al. (PP2-26) reported on diamond film growth in combustion flames using oxygen-ethane and oxygen-acetylene-hydrogen gas mixtures. Growth patterns and rates were found to

depend on the substrate position in the flame and the radial position of the substrate surface as measured from the flame axis. Other poster papers (PP2-11, PP2-12, PP2-14, PP2-16, PP2-18, PP2-19, PP2-21) were concerned with diamond film formation on various substrates (e.g., WC, TiC) using different techniques (microwave, thermal, ultra high vacuum electron cyclotron resonance) to obtain the gaseous species necessary for diamond film formation.

**Properties.** Yoshimura et al. (PP2-17) presented a paper on CVD diamond-coated cemented-carbide inserts that exhibited better wear and shock resistance in machining nonferrous metals, especially aluminum alloys, than the uncoated carbide. Ootake et al. (PP2-25) also showed that diamond films on a sintered diamond tool had much better wear resistance than the uncoated tools when cutting sintered  $Al_2O_3$ .

Yang et al. (PP2-24) described a method to polish diamond films by using iron or nickel polishing plates at low pressing pressures. This is analogous in many ways to procedures used in gem-quality polishing. No diamond fragments were observed, and it was proposed that the polishing occurs via a nonmechanical reaction involving the graphitization of diamond.

Obata and Morimoto (PP3-19) examined the thermal properties of diamond films formed by hot filament CVD. They concluded that such films were oxidation resistant below 600 °C in air and that absorbed hydrogen atoms played an important role in stabilizing the diamond film

surface. It was also reported that the coefficients of thermal expansion for the synthesized diamond films were approximately the same as that of natural diamond.

Beetz et al. (PP3-26) measured the thermal conductivity of diamond films grown by the hot filament CVD method and compared their values to those for single-crystal diamond as a function of temperature. The magnitude of the thermal conductivity of the films was less than that of the single crystal, but all of the curves exhibited the same characteristic shape. The observed differences were attributed to the small grains in the films and the presence of some graphite in the diamond films.

### Diamond Crystal Synthesis

**Processing.** Onodera et al. (PP3-02) have studied noncatalytic diamond synthesis at constant pressure and proposed that the transition temperatures of amorphous carbons are lower than spectroscopic graphite since diamond formation from amorphous carbon takes place via a species other than graphite. Hosomi et al. (PP3-03) showed that diamond crystals formed below the eutectic point of the metal (Fe,Co)-carbon diagram. Kondo and Sawai (PP3-04) presented a paper on the shock consolidation of fine diamond powders. They proposed stronger compacts of diamond can be fabricated by using nanocrystalline grains prepared by shock synthesis. Shige et al. (PP3-05) examined the sintering of diamond powder and proposed large and high quality diamond aggregates can be prepared by using small amounts of cobalt electrolessly deposited on the diamond powder followed by sintering under pres-

tures of about 8 GPa and temperatures of about 1,750°C. Akaishi et al. (PP2-23) also presented results on sintered diamond powders where it was shown that a Super Invar (iron-nickel alloy) additive produced superior compacts compared to those prepared by using Co or Ni additives.

**Properties.** Heath (PP3-09) described techniques to prepare tougher and more wear resistant polycrystalline diamond via sintering with emphasis on tailoring for specific areas of applications. Xu (PP3-10) described measurements using Raman spectra shifts to calculate components of stresses in diamond anvils. Tsuji et al. (PP3-11) presented results obtained with mirror-surfaced cBN single-crystal cutting tools soldered to steel shanks. Hardened steel could be cut with a very low surface roughness, but tool life was too short for practical use. Sugita et al. (PP3-12) described the etching of diamond and cBN via micro-sputtering and inlaying of the etched areas with gold. Yu and Li (PP3-14) presented results on sintered diamond composites showing that their thermal stability and wear resistance were dependent upon the phases present at grain boundaries. Iizuka (PP3-15) described techniques to synthesize tough cBN crystals for grinding wheels that yielded longer lives and remained sharp for long times due to the shape of the cBN crystals. Ueda and Yamamoto (PP3-16) presented a paper concerned with the effectiveness of cBN cutting tools bonded with  $\text{TiN-Al}_2\text{O}_3$  and  $\text{TiC-Al}_2\text{O}_3$ . It was reported that cutting performance of these bonding agents depended upon the material being cut and cutting speed.

Oikawa et al. (P3-23) presented results on cutting blades containing diamond particles formed by dispersion plating. Such blades were shown to be suitable for cutting ceramic substrates with high dimensional accuracy and possessed longer lives than resin-bonded blades.

## **CURRENT STATUS OF THE SCIENCE AND TECHNOLOGY FOR FABRICATING DIAMOND FILMS**

A substantial amount of research and development is being performed throughout the world to attempt to use diamond films in various industrial applications. The Japanese effort in the development and application of this technology is probably the largest of any single country. This effort consists of programs at national laboratories, universities, and numerous industrial companies, and it has been organized in a similar way to many other national research efforts. As is the case with much Japanese research, it is very much directed towards making and using diamond films, rather than developing theories and models to account for diamond film formation. In the following some important aspects of diamond film technology are discussed and assessed.

### **Theoretical Explanations for the Formation of Diamond Films**

The conditions that must be developed in the gas phase and at the surfaces of specimens in order to have diamond films nucleate and grow are not very well understood. The current status is such that it is

evident there are a number of gas compositions and maybe a variety of gaseous species from which diamond can be formed. Important species appear to be methyl radicals, methyl cations, acetylene, and hydrogen atoms, but the fact that diamond films were formed by using combustion flames, in  $O_2$ - $CH_4$  gas mixtures, and by sputtering graphite shows other conditions can be used to form diamond films. Mechanistic details are lacking. It is clear, however, that diamond films are formed at pressures and temperatures for which diamond is metastable. Hence, nucleation processes must play an important role. The programs of Angus (P1-03), Pate (P3-15), Messier (P1-02) and Badzian (P1-14), and Butler (P1-04) are directed towards developing further understanding of the important gaseous species, and these efforts are as advanced as any of the Japanese programs. Continued research in this area is critical if the gas compositions and gaseous species necessary for diamond film formation are to be defined and mechanisms are to be developed to describe diamond film nucleation and growth.

### Structures of Diamond Films

The structures of diamond films formed on various substrates to some extent are remarkably consistent. For example, these films are usually composed of columnar grains extending through the film with their longitudinal axes, which are often a (100) direction, normal to the substrate surfaces. These films may contain graphitic components and amorphous carbon, which often become more prevalent at high film growth rates. Questions arise with regards to structural defects within the individual columnar grains (e.g., twins, stacking

faults), orientations of the columnar grains, and especially the structures and compositions of the intergranular regions between the columnar grains. The data available suggest that the graphitic and amorphous carbon components are located in such regions, but the evidence is not conclusive. The interfaces between the substrates and the diamond films also are in need of definition. Glass (P3-10) has shown that for one set of conditions a  $\beta$ -SiC buffer layer was formed between the diamond film and a silicon substrate, but no such layer was observed when the gas composition was changed from 0.3 percent  $CH_4/H_2$  to 2 percent  $CH_4/H_2$ . The nature of this interface must be dependent on the properties of the substrate, such as structure and composition, as well as temperature and the composition of the gas.

While most diamond films possess the characteristics described in the preceding paragraph, films with different structures may be formed. The observation that surface facets of a particular shape appeared, disappeared, and reappeared (PP2-01) indicates new grains may be formed as the film thickens. Hence, all films may not contain columnar grains extending from the substrate to gas interface. In some cases a relatively few nuclei are formed upon a given substrate, and individual diamond crystals grow in directions both parallel and normal to the substrate surfaces. For sufficiently long deposition times the parallel growth must terminate as the crystals begin to impinge upon one another with the development of interfaces between the individual diamond crystals.

The structures of diamondlike films have not been described as well as the diamond films. Diamondlike films do not possess well-definable crystalline structure.

Their structures may be described as glassy, or microcrystalline, or perhaps amorphous. Depending upon the deposition conditions, diamondlike films can contain up to 40 atomic percent hydrogen. Diamondlike films are often formed at low substrate temperatures. Diamondlike films exhibit some of the same attractive properties as diamond films but at reduced levels. For example, the diamondlike films have Vickers hardnesses ranging from 2,000 to 5,000 compared to 10,000 for thick diamond films (P1-11) and for natural diamond.

More work certainly is required to further describe and understand the development of the morphologies and microstructures of diamond films. It is necessary to correlate these microstructures with the gas compositions and temperatures at which the films are formed. The magnitude of the current effort on work of this nature is greater in Japan than in the United States, but the caliber of the work described by Glass is equal to the best of that being done in Japan as represented by Sato (P1-15) and his coworkers at the National Institute for Research in Inorganic Materials (NIRIM).

Diamond films may be used in applications for wear resistance, and even heat sinks, without a thorough understanding or control of the interrelationships between substrate-gas composition-temperature and diamond film structure, but if diamond films are to be used as semiconductors structure control will be necessary. The production of films with columnar grains and very little graphitic or amorphous carbon components at acceptable growth rates will eventually be achieved. The problem of eliminating all grain boundaries and growing single-crystal diamond films on different substrates is much more difficult to overcome.

## **Processing Conditions for Fabrication of Diamond Films**

A very large number of papers and poster papers were involved with various techniques to produce diamond films. A number of gas compositions and temperatures for diamond deposition have been found. Different approaches for activating the gas, such as microwave, electron cyclotron resonance (ECR) microwave, hot filaments, and high current density dc synthesis, have been reported. Finally, diamond films have been formed in a combustion flame of an oxyacetylene torch. Growth rates of 100 to 150  $\mu\text{m/h}$  have been achieved. The areas covered with such films are small, usually on the order of a few square centimeters but in some cases about 100  $\text{cm}^2$  (PP2-07). Increased area coverage with uniform thickness and quality control represents an important required improvement in this technology.

In discussing deposition rates and coverages, it is worth noting that the maximum values for these parameters are not substantially greater than values presented at the Second Diamond Symposium in December 1987. In a recent announcement, the National Institute for Research on Inorganic Materials reported that in the past large-size diamond films were difficult to produce using plasma CVD techniques because their size was limited by the area over which the plasma could be generated (Ref 12). A system using two horizontally placed 1.5-kW microwave generators to allow control over the microwave output and the position of the plasma has been developed. This device produces a stable plasma 30 mm in width and 150 mm in length that can be moved laterally to deposit large-area films. In this device, 500-W

microwaves were used to generate a plasma at 800 to 900 °C in a source containing less than 1 percent methane in hydrogen. At a source gas feed rate of 100 to 200 SCCM, polycrystalline diamond with physical properties comparable to natural diamond was formed on silicon at a rate of 0.2  $\mu\text{m}/\text{h}$  over an area of 80  $\text{cm}^2$ . The point to be emphasized is that while the current maximum deposition rates and coverages are about 150  $\mu\text{m}/\text{h}$  and 100  $\text{cm}^2$ , respectively, these two parameters cannot be achieved concomitantly along with deposition of high-quality diamond.

Most of the work that has been done on processing has been empirical. The Japanese effort is vast compared to that in the United States. The first industrial applications of diamond films are beginning to emerge from this research involved with processing. For example, as will be discussed later, Asahi Industrial Diamond is using diamond films on drills and to make more wear resistant surfaces.

### **Applications of Diamond and Diamondlike Films**

As mentioned in a recent issue of the *New York Times* (Ref 13), diamond films, or diamondlike films, are beginning to reach the industrial marketplace. The precise status of the transfer of the diamond film technology to the marketplace, however, is not completely clear. Asahi Industrial Diamond has coated diamond films on drills, some dies, and some bearing surfaces. The areas of the surfaces that have been covered are small. Spalling of the diamond film is a problem. Asahi Industrial Diamond has apparently overcome this

spalling problem in the case of tungsten carbide, tungsten, and molybdenum substrates by using a heat treatment. Such coated hardware is being used by customers of Asahi Industrial Diamond with encouraging results. Nevertheless, the questions of cost versus tool lives are still in the process of being resolved.

Diamond and diamondlike films have also been used by Sumitomo Electric on diaphragms in tweeters of speakers. Diamond films have been deposited on alumina diaphragms via CVD to alter certain physical properties. For example, the velocity of sound and Young's modulus of an alumina diaphragm are 9.4 km/s and  $3.4 \times 10^{11}$  Pa, respectively, compared to 10 km/s and  $4.6 \times 10^{11}$  Pa for this diaphragm coated with 2  $\mu\text{m}$  of diamond. The diamondlike films have been used on titanium diaphragms.

It seems certain that the use of diamond films to increase tool lives will eventually become commonplace. Diamond crystals grown by the temperature gradient method have been used for years on cutting tools, but the capability to coat irregular-shaped surfaces with diamond films is an attractive feature of the vapor phase deposition process. Other applications such as heat sinks will also become economically feasible and still other applications will arise. At present, however, much of this progress will only come after significantly more research and development. There is still much to be learned about these films before they can be used in but a few limited applications. It will be necessary to differentiate between the properties of diamond and diamondlike films. The effects of graphitic and/or carbon components on

diamond film properties must be understood since the minimization of such components becomes more difficult at high film growth rates. Also these diamond and diamondlike films have been reported to be stable and functional to temperatures as high as 600 °C. The data used to support such statements have not been completely convincing. Long time exposures at elevated temperatures in different relevant environments followed by detailed microstructural and phase characterizations are necessary to define the temperatures and other conditions under which diamond films can be used without significant property changes.

### SYNTHETIC DIAMOND CRYSTALS

The fabrication of synthetic diamonds using variations of the temperature gradient method is now widespread. Work is currently being directed at developing modifications to this process whereby higher purity, increased size with less microstructural defects, and controlled orientation are goals to be achieved with less cost. The applications for these type of diamonds consist of abrasive applications, wire drawing dies, cutting tools, anvils, heat sinks, and optical components. In addition to the needs of improving quality and lowering costs, research is being performed to determine the effect of impurities on the electronic structure of diamond. Controlled doping of synthetic diamonds probably will result in increased applications for these materials. Yazu (P2-02) and coworkers at Sumitomo Electric Industries are the leaders of this type of research in Japan.

### CUBIC BORON NITRIDE

Cubic boron nitride has some rather attractive properties. It is hard, being the second hardest material next to diamond, and has a bandgap at room temperature greater than 6.6 eV compared to 5.48 eV for diamond (Ref 14). Mishima et al. (P2-08) reported the bandgap of cBN to be at least 6.4 eV. It is metastable under normal use conditions of temperature and pressure and can be prepared by the temperature gradient method. For example, typical conditions for fabrication could be 55 kbar at 1,700 °C using LiCaBN<sub>2</sub> as a solvent. It has also been prepared as a film by thermally activated rf plasma CVD (Ref 15) and by physical vapor deposition (PVD) (Ref 16). In the case of CVD the gas was 1 percent B<sub>2</sub>H<sub>6</sub> and 1 percent NH<sub>3</sub> in hydrogen at 67 to 160 Pa. The specimen (silicon) temperature was 800 °C and filament temperatures varied between 1,200 and 2,000 °C. It can also be prepared by reaction sintering under high pressure where hBN is transformed to cBN. Because of its wide bandgap and since it can behave as either a n- or p-type semiconductor, a significant amount of research is being performed on this material in Japan, with the group led by Mishima (P2-08) at NIRIM being the leaders. These investigators have fabricated a light-emitting diode (LED) using cBN that can emit an ultraviolet light with much shorter wavelength than other LEDs.

The structures of cBN crystals and films have not been as extensively examined as diamond. Seed crystals have been used to control orientations but without much success.



Cubic boron nitride is used and has potential uses in applications very similar to diamond. It does not, however, react with iron as does diamond. Furthermore, in the oxidation of diamond, volatile products are formed, whereas in the oxidation of cBN the products can be boron oxides, which have been proposed to provide some protection. As in the case of diamond, the effects of temperature and various environments on cBN have not been examined very extensively, and much more thorough investigations are necessary.

The investigations of cBN in Japan will continue. Properties of crystals formed at high pressures and temperatures will continue to be investigated and described. Emphasis will be placed on higher growth rates, controlled purity and doping, and the quality of crystalline structures. In this respect fabrication procedures to grow films will receive attention with activated CVD processes having high priority.

## CONCLUDING REMARKS

Diamond technology and research in Japan are well described in two recently published books, *Diamond Thin Film Technology* (Ref 14) and *Synthesis Technology of Diamond and Its Applications and Examples* (Ref 17). These books are in Japanese. Chapter titles and authors are presented in Appendix C. Much of the material presented by the Japanese authors at the First International New Diamond Conference is covered in these two books. Chapters in these books have been prepared by Japanese experts on various topics related to diamond film synthesis.

The research and development in Japan on diamond films and on diamond synthesis in general is extensive. Basic

research is being done, but it is not more advanced nor more sophisticated than that in the United States. The large difference arises when one considers empirical development where numerous Japanese investigators are working to produce diamond in different forms for various applications. The corporate investment is larger in Japan than in the United States. Kobe Steel has announced that it will establish a new research center in the United States at which research and development will be conducted on diamond films and polymer materials (Ref 18). It is just a matter of time until many Japanese industries begin to use this technology to make new and improved products. It is important to emphasize that they are not at that stage currently. The first significant applications of diamond films will be to improve performances of tools and bearing surfaces. Within the next 6 months information should be available to show if the current technology is adequate for such applications, or if some further improvements are required. For other applications it is apparent more research and development will be required to improve diamond film structure at higher deposition rates and coverages and to characterize various properties. The technology level for cBN films is much below that of diamond, but continued progress in the fabrication and characterization of this material by Japanese investigators can be expected.

The same remarks are generally applicable to synthetic diamond and cBN crystals with the exception that not as many institutions and companies are involved in the cBN work as compared to diamond research and development.

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## REFERENCES

1. H.M. Strong and R.E. Hannerman, "Crystallization of diamond and graphite," *J. Chem. Phys.* **46**, 3668-76 (1967).
2. R.H. Wentorf, *J. Phys. Chem.* **75**, 1833 (1971).
3. B.V. Derjaguin and D.V. Fedoseev, *Nauka*, Moscow (1977).
4. B.B. Spitsyn, L.L. Bouilov, and B.V. Derjaguin, *J. Crystal Growth* **52**, 219 (1981).
5. S. Matsumoto, Y. Sato, M. Kamo, and N. Setaka, *Jpn. J. Appl. Phys.* **21**, L183 (1982).
6. M. Kamo, Y. Sato, S. Matsumoto, and N. Setaka, *J. Crystal Growth* **62**, 642 (1983).
7. S.J. Harris, A.M. Weiner, and T.A. Perry, *Appl. Phys. Lett.* **52**, 2043 (1988); F.G. Celii, P.E. Pehrsson, H.T. Wang, and J.E. Butler, *Appl. Phys. Lett.* **52**.
8. A. Zhu, A.R. Badzian, and R. Messier, submitted to *J. Mat. Res.*
9. W. Zhu, C. Randall, A.R. Badzian, and R. Messier, submitted to *J. Vac. Sci. Technol.*
10. C.P. Chang, D.L. Flamm, D.E. Iblotson, and J.A. Mucha, *Appl. Phys. Lett.* **63**, 1744 (1988).
11. A.R. Badzian, T. Badzian, R. Roy, R. Messier, and K. Spear, *Mat. Res. Bull.* **23**, 531 (1988).
12. *Nikkan Kogyo Shinbun*, 26 October 1988.
13. *New York Times*, 20 October 1988.
14. N. Setaka, editor, *Diamond Thin Film Technology* (Sogo Gyutsu Center, Tokyo, 1988).
15. H. Saitoh, T. Ishiguro, and Y. Ichinose, *New Diamond* **3**(1), 34 (1978).
16. K. Inagawa, *J. Vac. Sci. Technol.* **A5**, 2696 (1987).
17. N. Setaka, O. Matsumoto, Y. Namba, and S. Yazu, editors, *Synthesis Technology of Diamond and Its Applications and Examples* (Oyo Gijutsu Shuppan Kobushikigaishu, Tokyo, 1987).
18. *Nikkan Kogyo Shinbun*, 6 October 1988.

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## **Appendix A**

### **PAPERS PRESENTED AT THE FIRST INTERNATIONAL CONFERENCE ON THE NEW DIAMOND SCIENCE AND TECHNOLOGY**

#### **PI SOME MECHANICAL PROPERTIES OF DIAMOND - A PERSPECTIVE VIEW**

**C.A. Brookes, E.J. Brookes, V.R. Howes**  
Department of Engineering Design and Manufacture  
University of Hull, Hull, HU6 7RX, U.K.

#### **P1-01 DIAMOND FILMS: SYNTHESIS, PROPERTIES, APPLICATIONS**

**Boris V. Spitsyn**  
Institute of Physical Chemistry AN U.S.S.R.  
Leninsky Prospect 31, Moscow 117915, U.S.S.R.

#### **P1-02 RECENT WORK ON VAPOR DIAMOND GROWTH IN THE U.S.**

**Russell Messier, Andrzej Badzian, and Walter A. Yarbrough**  
Materials Research Laboratory  
The Pennsylvania State University  
University Park, PA 16802

#### **P1-03 STUDIES OF AMORPHOUS HYDROGENATED "DIAMONDLIKE" HYDROCARBONS AND CRYSTALLINE DIAMOND**

**John C. Angus and Richard W. Hoffman**  
Case Western Reserve University  
Cleveland, OH

**Paul H. Schmidt**  
Digital Equipment Corporation  
Shrewsbury, MA

#### **P1-04 IN-SITU DETECTION OF GASEOUS SPECIES IN THE FILAMENT-ASSISTED DIAMOND GROWTH ENVIRONMENT**

**F.G. Celii, P. Pehrsson, H.-T. Wang, H.H. Nelson, and J.E. Butler**  
Chemistry Division  
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**P1-05 STUDY OF THE DIAMOND DEPOSITION FROM GAS PHASE USING TRANSMISSION ELECTRON MICROSCOPY**

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**P1-06 THE NUCLEATION AND GROWTH OF THIN DIAMOND FILMS**

K.V. Ravi, M. Peters, L. Plano, S. Yokota, and M. Pinneo  
Crystallume  
125 Constitution Avenue  
Menlo Park, CA 94025

**P1-07 ELECTROCONDUCTIVITY OF POLYCRYSTALLINE DIAMOND FILMS**

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**P1-08 DIAMOND AND DIAMOND LIKE CARBON FILMS BY ION BEAM SPUTTER DEPOSITION TECHNIQUE**

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**P1-09 SYNTHESIS OF DIAMOND USING COMBUSTION FLAME IN THE ATMOSPHERE**

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**P1-10 THICK DIAMOND FILMS GROWTH BY DC DISCHARGE PLASMA CHEMICAL VAPOR DEPOSITION AND THEIR CHARACTERIZATION**

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**P1-11 THICK DIAMOND FILM SYNTHESIS BY DC PLASMA JET CVD**

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**P1-12 DIAMOND SYNTHESIS IN A MW PLASMA JET**

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**P1-13 DEPOSITION OF DIAMOND FILM FROM THE O<sub>2</sub>-CH<sub>4</sub> SYSTEM**

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**P1-14 CRYSTALLIZATION OF DIAMOND BY MICROWAVE PLASMA ASSISTED CHEMICAL VAPOR DEPOSITION**

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**P1-15 FORMATION AND STRUCTURAL FEATURES OF NEEDLE-LIKE DIAMOND**

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**P2-01 SPECTROSCOPIC STUDIES OF SYNTHETIC DIAMONDS GROWN BY THE TEMPERATURE GRADIENT METHOD**

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**P2-02 SOME THERMAL AND OPTICAL PROPERTIES OF SYNTHETIC DIAMONDS**

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**P2-03 THERMAL PROPERTIES OF BORON PHOSPHIDE SINGLE CRYSTALLINE WAFERS**

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1-1 Namiki, Tsukuba-shi, Ibaraki, Japan

S. Okaya, F. Muta, and T. Koshiro  
Rigaku Keisoku Co., Ltd.  
3-9-12 Matsubara-cho, Akishima-shi, Tokyo, Japan

**P2-04 PLASMA DEPOSITED DIAMOND-LIKE FILMS FOR IR DEVICE APPLICATIONS**

R.S. Yalamanchi, C. L. Nagendra, and G.K.M. Thutupalli  
Indian Space Research Organisation (ISRO)  
ISRO Satellite Centre  
Airport Road, Bangalore-560017, India

**P2-05 MECHANICAL PROPERTIES OF DIAMONDLIKE CARBON FILMS**

Nobuaki Shohata and Kazutaka Fujii  
Fundamental Research Laboratories

Shigeki Hoshino  
Resource and Environment Research Laboratories

Hiroataka Yamaguchi, Yuji Tsukamoto, and Masahiro Yanagisawa  
Microelectronics Research Laboratories

NEC Corporation  
4-1-1, Miyazaki, Miyamae-ku  
Kawasaki, Kanagawa 213, Japan

**P2-06 THERMISTOR MADE OF DIAMOND THIN FILM**

H. Nakahata, H. Shiomi, T. Imai, Y. Nishibayashi and N. Fujimori  
Sumitomo Electric Industries, Ltd.  
1-1-1. Koyakita, Itami, Hyogo 664, Japan

**P2-07 BLUE AND GREEN CATHODOLUMINESCENCE OF VAPOUR DEPOSITED DIAMOND FILMS FORMED BY PLASMA CVD AND ITS COMPARISON WITH BULK DIAMOND**

H. Kwarada, Y. Yokota, K.S. Mar, J. Suzuki, and A. Hiraki  
Faculty of Engineering, Osaka University  
Suita, Osaka 565, Japan

K. Nishimura  
Osaka Diamond Industrial Co.  
Sakai, Osaka 593, Japan

T. Ito  
Planning and Development Center  
Idemitsu Petrochemical Co. Ltd.  
Kimitsu, Chiba 299-02, Japan

**P2-08 CUBIC BORON NITRIDE PN JUNCTION DIODE MADE AT HIGH PRESSURE AS A HIGH TEMPERATURE DIODE AND AN ULTRAVIOLET LED**

O. Mishima, S. Yamaoka, O. Fukunaga, J. Tanaka and K. Era  
National Institute for Research in Inorganic Materials  
1-1 Namiki, Tsukuba-shi, Ibaraki 305, Japan

**P2-09 MECHANISM OF NUCLEATION PROCESS OF DIAMOND**

Masao Wakatsuki  
Institute of Materials Science  
University of Tsukuba  
Tsukuba, Ibaraki 305, Japan

**P2-10 HIGH PRESSURE SYNTHESIS OF CUBIC BORON NITRIDE, SINGLE AND POLYCRYSTALS USING LARGE SCALE BELT APPARATUS**

Osamu Fukunaga  
Dept. Inorganic Materials  
Tokyo Institute of Technology  
O-okayama, Meguro-ku, Tokyo 152

**P2-11 DYNAMIC HIGH PRESSURE CONSOLIDATION OF DIAMOND POWDERS**

Akira B. Sawaoka and Tamotsu Akashi  
Center for Ceramics Research  
Tokyo Institute of Technology  
Midori, Yokohama 227, Japan

**P2-12 THE MANUFACTURE AND APPLICATION OF DE BEERS LARGE CRYSTAL SYNTHETIC DIAMOND**

Dr. R.C. Burns  
De Beers Diamond Research Laboratory  
P.O. Box 916  
Johannesburg 2000 South Africa

**P2-13 HIGH PRESSURE SINTERING OF DIAMOND BY COBALT INFILTRATION**

Kazuhito Uehara and Susumu Yamaya  
Toshiba Tungaloy Co., Ltd.  
1-7, Tsukagoshi, Kawasaki-City 210, Japan

**P2-14 PREPARATION OF c-BN SINTERED COMPACT BY REACTION SINTERING UNDER HIGH PRESSURE**

Hideaki Itoh, Tsuneaki Matsudaira, and Shigeharu Naka  
Synthetic Crystal Research Laboratory  
Faculty of Engineering, Nagoya University  
Furo-cho, Chikusa-ku, Nagoya 464, Japan

**P2-15 THE INCREASE OF THE GROWTH RATE WHEN GROWING THE SYNTHETIC DIAMONDS**

N.V. Novikov  
The Research Institute for Superhard Materials of the Ukrainian S.S.R.

**P2-16 CRYSTAL GROWTH OF CUBIC BORON NITRIDE USING  $\text{Li}_3\text{BN}_2$  SOLVENT AND MORPHOLOGY OF THE GROWN CRYSTAL**

M. Kagamida\*, H. Kanda, M. Akaishi, A. Nukui, T. Osawa, and S. Yamaoka  
National Institute for Research in Inorganic Materials  
1-1 Namiki, Tsukuba-shi, Ibaraki 305, Japan  
\*On leave from Onoda Cement Co., Onoda-shi, Yamaguchi, Japan

**P2-17 MICROSTRUCTURE OF BORON ATOM DISTRIBUTION AND HEAT RESISTANCE IN THE AGGREGATE CRYSTAL OF BORON-COATED DIAMOND**

Su Wenhui and He Lanying  
Group of Solid State Physics, Dept. of Physics  
Jilin University  
Changchun, P.R. China

**P2-18 EFFECT OF ADSORBED GASES ON THE RAW MATERIAL ON THE CONDITION OF DIAMOND FORMATION**

H. Uchikawa, H. Hagiwara, and K. Nakamura  
Ceramics Research Laboratory  
Onoda Cement Co. Ltd.  
1-1-7, Toyosu, Koto-ku, Tokyo, Japan

**P2-19 NEW WAY OF LOWER HP DIAMOND GROWTH**

A. Niedbalska, A. Szymanski, and S.A. Zalewski  
Mattech Ltd. Co., - Advanced Technology  
6/14 Krucza Str., Apt. 113, 00-537 Warszawa, Poland

**P3-01 NEW DIAMOND FORUM - A RESUME OF THE PAST OR A CHALLENGE FOR THE FUTURE OF DIAMOND/CBN TOOLS**

H. Wapler  
De Beers Industrial Diamond Division  
Charters, Sunninghill, Ascot, Berkshire, England



**P3-02 REACTIVITY AND WEAR OF DIAMOND AND CBN**

H.P. Bovenkerk  
General Electric Company  
P.O. Box 568  
Worthington, OH 43085

**P3-03 STRENGTH PROPERTIES AFFECTING RELIABILITY OF DIAMOND TOOL**

Shoichi Shimada, Naoya Ikawa, Giichi Ohmori, and Junichi Uchikoshi  
Department of Precision Engineering, Osaka University  
2-1 Yamada-Oka, Suita, Osaka 565, Japan

**P3-04 MEASUREMENT ON CUTTING EDGE RADIUS OF SINGLE POINT DIAMOND TOOL WITH NEWLY DEVELOPED SEM**

S. Asai  
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Y. Taguchi  
Elionix Inc.  
3-7-6, Motoyokoyama-cho, Hachioji-shi, Tokyo 192, Japan

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Saitama University  
255 Ookubo, Urawa-shi, Saitama 336, Japan

A. Kobayashi  
Ibaraki Polytechnic College  
864-4 Suifu-cho, Mito-shi, Ibaraki 310, Japan

**P3-05 AN ULTRAPRECISION DIAMOND CUTTING TOOL WITH 50 nm CORNER RADIUS ROUNDNESS FOR ASPHERIC TURNING**

K. Nishimura, K. Obata, T. Chujo, and H. Yoshinaga  
Osaka Diamond Ind. Co. Ltd.  
2-80, Ohtori-kita, Sakai 593, Japan

S. Shimada and N. Ikawa  
Faculty of Engineering, Osaka University  
Suita 565, Japan

**P3-06 ION BEAM FORMING AND SHARPENING OF DIAMOND TOOLS HAVING A SMALL APEX ANGLE**

Iwao Miyamoto  
Science University of Tokyo  
Noda, Chiba 278, Japan

**P3-07 CUTTING PERFORMANCE OF DIAMOND DEPOSITED TOOL FOR Al-18<sub>mass</sub>%Si ALLOY**

Masaru Yagi  
Toshiba Tungaloy Co., Ltd.  
8 Shinsugita-cho, Isogo-ku, Yokohama, Japan

**P3-08 BONDING OF DIAMOND BY REFRACTORY METAL COATING**

Chien-Min Sung  
Norton Christensen, Diamond Technology Center  
2532 South 3270 West  
Salt Lake City, UT 84119

**P3-09 THE CHOICE OF DIAMOND FOR SOME SCIENTIFIC APPLICATIONS**

M. Seal  
D. Drukker & Zn. N.V.  
PO Box 15120  
1001 MC Amsterdam, The Netherlands

**P3-10 ELECTRON MICROSCOPY OF DIAMOND FILMS AND DIAMOND SUBSTRATE INTERFACES**

J.T. Glass, B.E. Williams, and R.F. Davis  
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North Carolina State University  
Raleigh, NC 27695

K. Kobashi  
Electronics Technology Center, Kobe Steel, Ltd.  
Kobe 651, Japan

**P3-11 ULTRA-HIGH-VOLTAGE TRANSMISSION ELECTRON MICROSCOPE OBSERVATION OF DIAMOND PARTICLES GROWN FROM PLASMA-ASSISTED CVD**

King Sheng Mar, Hiroshi Kwarada, Jun-ichi Suzuki, and Akio Hiraki  
Faculty of Engineering

Hiroto Mori and Hiroshi Fujita  
Research Center for Ultra-High-Voltage Electron Microscopy

Osaka University  
Suita-shi, Osaka 565, Japan

**P3-12 ETCHING CHARACTERISTICS OF CARBON FILMS BY THE RF PLASMA**

Kenji Kobayashi, Yoshihito Shimada, Nobuki Mutsukura, and Yoshio Machi  
Department of Electronic Engineering  
Faculty of Engineering  
Tokyo Denki University  
Chiyoda-ku, Tokyo 101, Japan

**P3-13 FORMATION OF NITROGEN PAIR IN SYNTHETIC DIAMOND DURING GROWTH**

Hisao Kanda, Toshikazu Ohsawa, and Shinobu Yamaoka  
National Institute for Research in Inorganic Materials  
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**P3-14 ELECTRON MICROSCOPE STUDY OF LATTICE DEFECTS IN NATURAL DIAMOND**

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A.R. Lang  
H.H. Wills Phys. Lab.  
Univ. of Bristol  
Bristol BS8 1TL, U.K.

**P3-15 THE ELECTRONIC STRUCTURE OF DIAMOND SURFACES**

B.B. Pate, J.C. Hwang, J. Woicik, and I. Lindau  
Stanford Synchrotron Radiation Laboratory  
Stanford University  
Stanford, CA 94309

**P3-16 PHYSICAL PROPERTIES OF LARGE SYNTHETIC DIAMONDS**

S. Satoh, H. Sumiya, K. Tsuji, and S. Yazu  
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Sumitomo Electric Industries Ltd.  
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**P3-17 ESE AND CW-ESR STUDIES OF SYNTHETIC DIAMOND CRYSTALS: DISTRIBUTION OF NITROGEN AND NICKEL**

J. Isoya  
University of Library and Information Science  
Kasuga 1-2  
Tsukuba-City 305, Japan

C.P. Lin, M.K. Bowman, and J.R. Norris  
Chemistry Division, Argonne National Laboratory  
Argonne, IL 60439

S. Yazu and S. Sato  
Itami Laboratory, Sumitomo Electric Industries, Ltd.  
Itami-City, Hyogo-ken 664, Japan

**P3-18 COLOR CENTERS IN SYNTHETIC Ib DIAMONDS AND THEIR APPLICATION TO OPTO-ELECTRONICS**

**Y. Nishida, Y. Mita, S. Okuda, and T. Mihara**  
Material Physics, Engineering Science, Osaka University  
1-1 Machikaneyama, Toyonaka 560, Osaka

**R. Kato and M. Ashida**  
Physics, Faculty of Science, Kyoto University  
Kitashirakawa, Oiwake-cho, Sakyo-ku 606, Kyoto

**S. Sato and S. Yazu**  
Itami Research Laboratories, Sumitomo Electric Industries  
Itami 664, Hyogo

**P3-19 MELTING OF DIAMOND**

**Motohiro Togaya**  
Department of Material Physics  
Faculty of Engineering Science, Osaka University  
Toyonaka, Osaka 560, Japan

## **Appendix B**

### **POSTER PAPERS PRESENTED AT THE FIRST INTERNATIONAL CONFERENCE ON THE NEW DIAMOND SCIENCE AND TECHNOLOGY**

#### **PP2-01 MORPHOLOGY AND GROWTH OF DIAMOND FILMS**

Koji Kobashi, Kozo Nishimura, Koichi Miyata, and Yoshio Kawate  
Electronics Technology Center, Kobe Steel, Ltd.  
1-5-5, Takatsukadai, Nishi-ku, Kobe 673-02, Japan

Jeffrey T. Glass  
Department of Materials Science and Engineering  
North Carolina State University  
Raleigh, NC 27695-7907

#### **PP2-02 GASEOUS PHASE SYNTHESIS OF DIAMOND AND ITS PRACTICAL APPLICATION**

Fuminori Okuzumi, Junichi Matsuda, Kazuo O-oka  
R&D Division, Asahi Diamond Industrial Co.  
185, Kuji Takatsu-ku, Kawasaki-shi 213, Japan

#### **PP2-03 SELECTIVE DEPOSITION OF DIAMOND CRYSTALS**

K. Hirabayashi, K. Ikoma, Y. Taniguchi, and N.I. Kurihara  
Canon Inc.  
Atsugi-shi, Kanagawa 243-01, Japan

#### **PP2-04 CARBURIZING AND DIAMOND DEPOSITION ON TITANIUM AND MOLYBDENUM SUBSTRATES WITH PLASMA JETS UNDER REDUCED PRESSURE**

Osamu Matsumoto and Ryuichi Furukawa  
Department of Chemistry, Aoyama Gakuin University  
Chitosedai, Setagaya-ku, Tokyo 157, Japan

#### **PP2-05 PREPARATION OF POLYCRYSTALLINE DIAMOND FILMS IN A PARALLEL-PLATE RF DEPOSITION SYSTEM**

P. Wood and T. Wydeven  
Opto Films  
Sunnyvale, CA 94089

O. Tsuji  
SAMCO International, Inc.  
33 Tanakamiya-cho, Takeda  
Fushimi-ku, Kyoto 612, Japan

**PP2-06 LARGE AREA CVD OF DIAMOND FILMS MAGNETO-MICROWAVE PLASMA AT LOW PRESSURE**

Jun-ichi Suzuki, Hiroshi Kwarada, King-Sheng Mar, Yoshiro Yokota, and Akio Hiraki  
Faculty of Engineering, Osaka University  
Yamada-oka 2-1, Suita, Osaka, Japan

**PP2-07 LARGE AREA DIAMOND DEPOSITION BY MICROWAVE PLASMA CVD**

K. Ishibori and Y. Ohira  
Denki Kogyo Co., Ltd.  
4052-1, Sakuradai, Nakatsu  
Aikawa-cho, Aiko-gun, Kanagawa-ken 243-03, Japan

**PP2-08 THE SYNTHESIS OF DIAMOND ON POLYCRYSTALLINE GRAPHITE SUBSTRATE WITH THERMAL CHEMICAL VAPOUR DEPOSITION**

Jin Zengsun, Huang Fuping, Lu Xianyi, Qu Chenglin, and Zou Guangtian  
Institute of Atomic and Molecular Physics, Jilin University  
Changchun, China

**PP2-09 ENLARGEMENT OF MICROWAVE PLASMA REGION AND DIAMOND DEPOSITION AREA**

M. Kamo and Y. Sato  
National Institute for Research in Inorganic Materials  
1-1 Namiki, Tsukuba, Ibaraki 305, Japan

F. Takamura  
New Japan Radio Co. Ltd.  
2-1-1 Fukuoka, Kamifukuoka, Saitama 356, Japan

**PP2-10 DEPOSITION OF DIAMOND FROM  $\text{CH}_4$ - $\text{H}_2$  PLASMA AND  $\text{CO-H}_2$  PLASMA IN MICROWAVE DISCHARGE**

Hiroaki Toshima, Toshiro Kotaki, Youichi Yaguchi, and Yuji Amada  
Namiki Precision Jewel Co. Ltd.  
Shinden, Adachi-ku, Tokyo 123, Japan

Osamu Matsumoto  
Aoyama Gakuin University  
Chitosedai, Setagaya-ku, Tokyo 157, Japan

**PP2-11 MULTI-SHAPED AND HYBRID DIAMOND PARTICLES BY VAPOR PHASE METHOD**

K. Komaki, M. Yanagisawa, I. Yamamoto, K. Arashida, and T. Fujimaki  
Showa Denko K.K.  
Central Research Laboratory  
2-24-25 Tamagawa, Ohta-ku, Tokyo 146, Japan

**PP2-12 DIAMOND DEPOSITION BY MEANS OF TANTALUM FILAMENT ON WC-Co ALLOY AND OTHER HARD MATERIALS**

Hideaki Matsubara and Junji Kihara  
RCAST of the University of Tokyo  
4-6-1 Komaba Meguro-ku, Tokyo 153, Japan

**PP2-13 TEXTURE OF VAPOR DEPOSITED DIAMOND FILMS AS REVEALED BY PLASMA-ETCHING**

C. Hata  
Hoya Corporation  
3-3-1 Musashino, Akishima, Tokyo 196, Japan

M. Kamo and Y. Sato  
National Institute for Research in Inorganic Materials  
1-1 Namiki, Tsukuba, Ibaraki 305, Japan

**PP2-14 EFFECT OF SOME ADDITIVES TO THE SYSTEM  $\text{CH}_4\text{-H}_2$  ON DIAMOND DEPOSITION BY MICROWAVE PLASMA CVD**

Chia-Fu Chen and Yen. C. Huang  
Metallic Materials Dept., Faculty of Technology  
Tokai University

Satoru Hosomi and Isao Yoshida  
The Ishizuka Research Institute, Ltd.  
Hiratsuka, Japan

**PP2-15 STRUCTURE FEATURES OF DIAMOND FILMS SYNTHESIZED BY THERMAL CVD**

Zou Guangtian, Jin Zengsun, Kang Hanqing, Lu Xianyi, Huang Fuping, and Qu Chenglin  
Institute of Atomic and Molecular Physics, Jilin University  
Changchun, China

**PP2-16 DIAMOND SYNTHESIS BY THE MICROWAVE PLASMA CVD METHOD USING A MIXTURE OF CARBON MONOXIDE AND HYDROGEN GAS**

Toshimichi Ito, Atsuhiko Masuda, Yuji Eto, and Kazuomi Ito  
Idemitsu Petrochemical Co., Ltd.  
12-18 Ginza 4-chome  
Chuo-ku, Tokyo 104 Japan

Kichisuke Nishimoto  
Osaka City University  
3-3-138, Sugimoto Sumiyoshi-ku, Osaka 558, Japan

**PP2-17 CHARACTERISTICS OF CVD DIAMOND COATED INSERTS**

Hironori Yoshimura and Kei Nakahara  
Tokyo Plant of Mitsubishi Metal Corporation  
1-27-20, Nishishinagawa, Shinagawa, Tokyo 141, Japan

Hiroaki Yamashita and Noribumi Kikuchi  
Central Research Institute of Mitsubishi Metal Corporation  
1-297, Kitabukuro, Omiya, Saitama 330, Japan

**PP2-18 PREPARATION OF DIAMOND-LIKE FILMS BY UHV-ECR-CVD**

I. Nagai, A. Ishitani, and H. Kuroda  
Research Development Corporation of Japan  
Kuroda Solid Surface Project  
1-1, Sonoyama 1-chome  
Otsu, Shiga 520, Japan

**PP2-19 GROWTH OF DIAMOND ON SINGLE CRYSTAL OF TITANIUM CARBIDE**

Mutsukazu Kamo, Shigeki Otani, and Yoichiro Sato  
National Institute for Research in Inorganic Materials  
1-1 Namiki, Tsukuba, Ibaraki 305, Japan

Satoshi Aoki  
Noritake Co. Ltd.  
300 Higashiyama, Miyoshi, Nishikamo, Aichi 470-02, Japan

**PP2-20 NUCLEATION PROCESS OF DIAMOND BY PLASMA CVD**

S. Yugo and T. Kumura  
University of Electro-Communications  
1-5-1 Chofugaoka  
Chofu-shi, Tokyo 182, Japan

**PP2-21 RAPID GROWTH OF DIAMOND FILMS BY ARC DISCHARGE PLASMA CVD**

Fumio Akatsuka and Yoichi Hirose  
Department of Electrical Engineering and Electronics  
Nippon Institute of Technology  
Miyashiro, Minami-Saitama, Saitama 345, Japan

**PP2-22 ON GROWTH OF DIAMOND THIN FILMS BY CVD AND THEIR CHARACTERIZATION**

Hou Li, Qi Lichang, Yang Peichun, and Pu Xin  
Research Institute of Synthetic Crystals  
Beijing, China

**PP2-23 THERMAL PROPERTY OF THE SINTERED DIAMOND WITH SMALL AMOUNT OF METAL**

Minoru Akaishi, Toshikazu Ohsawa, and Shinobu Yamoaka  
National Institute for Research in Inorganic Materials  
1-1 Namiki, Tsukuba, Ibaraki 305, Japan

Osamu Fukunaga  
Faculty of Engineering, Tokyo Institute of Technology  
2-12-1, O-okayama, Meguro-ku, Tokyo 152, Japan



**PP2-24 POLISHING OF DIAMOND FILM WITH METAL**

Cheng-Feng Yang, Hitoshi Tokura, and Masanori Yoshikawa  
Faculty of Engineering, Tokyo Institute of Technology  
2-12-1, O-okayama, Meguro-ku, Tokyo 152, Japan

**PP2-25 DEPOSITION OF A DIAMOND FILM ON A SINTERED DIAMOND SURFACE AND ITS APPLICATION TO A CUTTING TOOL**

Naoto O-otake, Hitoshi Tokura, Masanori Yoshikawa, and Cheng-Feng Yang  
Faculty of Engineering, Tokyo Institute of Technology  
2-12-1, O-okayama, Meguro-ku, Tokyo 152, Japan

**PP2-26 DIAMOND GROWTH IN COMBUSTION FLAMES**

K.A. Snail and L.M. Hanssen  
Code 6522, Optical Sciences Division  
Naval Research Laboratory  
Washington, DC 20375-5000

W.A. Carrington  
Dept. of Electrical Engineering  
University of Virginia  
Charlottesville, VA 22906

D.B. Oakes and J.E. Butler  
Code 6174, Chemistry Division  
Naval Research Laboratory  
Washington, DC 20375-5000

**PP3-01 THE NUCLEATION BEHAVIOR OF DIAMOND CRYSTAL WITH THE PARTICIPATION OF NiMnCo CATALYST**

Yang Zongqing and Zhao Jianzhong  
Research Institute for Abrasives and Grinding  
Ministry of Machinery and Electronic Industry  
No. 121 Huashan Str.  
Zhengzhou, China

**PP3-02 SYNTHESIS OF DIAMOND FROM AMORPHOUS CARBON UNDER STATIC HIGH PRESSURE**

Akifumi Onodera, Koji Higashi, and Yasushi Irie  
Faculty of Engineering Science, Osaka University  
Toyonaka, Osaka 560, Japan

**PP3-03 DIAMOND FORMATION BY A SOLID STATE REACTION**

Satoru Hosomi, Yoshiaki Nakamura, and Shigeru Tanaka  
Tomei Diamond Company, Ltd.  
1-3-2, Nishi-Yawata, Hiratsuka, Kanagawa 254, Japan

**PP3-04 DIAMOND COMPACT OF NANO-SIZE GRAINS**

Ken-ichi Kondo and Sumiichi Sawai  
Research Laboratory of Engineering Materials  
Tokyo Institute of Technology  
Nagatsuta, Midori, Yokohama 227, Japan

**PP3-05 SINTERING OF DIAMOND POWDER ELECTROLESS-PLATED WITH Co METAL**

T. Shige, S. Endo, F.E. and Fujita  
Research Center for Extreme Materials, Osaka University  
Toyonaka, Osaka 560, Japan

Y. Tomii  
Department of Metal Science & Technology, Faculty of Engineering  
Kyoto University, Kyoto 606, Japan

**PP3-06 EFFECT OF RECRYSTALLIZED GRAPHITE ON THE NUCLEATION OF DIAMOND IN FILM GROWTH REACTION**

Wang Guangzu, Zheng Zhou, and Chen Lun  
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Zhengzhou, Henan, China

**PP3-07 MgO INTERFEROMETRIC SENSOR FOR HIGH PRESSURE MEASUREMENT UNDER HIGH TEMPERATURE**

N.M. Balzaretti, J.T.N. Medeiros, and J.A.H. Da Jornada  
Instituto de Fisica, Universidade Federal do Rio Grande do Sul  
91500 Porto Alegre-RS-Brasil

**PP3-08 MANUFACTURE OF PDC FOR CUTTING TOOLS**

Qi Zengdu and Zou Junxue et al.  
Shanghai Institute of Ceramics  
Academia Sinica

**PP3-09 NEW DEVELOPMENTS IN THE SYNTHESIS OF POLYCRYSTALLINE DIAMOND CUTTING TOOLS AND THE SELECTION OF PROPERTIES FOR SPECIFIC APPLICATIONS**

Dr. P.J. Heath  
De Beers Industrial Diamond Division  
Technical Service Centre  
Ascot, England

**PP3-10 THE STRESS DISTRIBUTION IN A DIAMOND ANVIL AT 5.5 MILLION ATMOSPHERES**

Ji-An Xu  
Hawaii Institute of Geophysics  
2525 Correa Rd.  
Honolulu, HI 96822

**PP3-11 THE CUTTING PERFORMANCE OF THE CBN SINGLE CRYSTAL IN PRECISION CUTTING OF HARDENED STEELS**

K. Tsuji, J. Degawa, and S. Yazu  
Itami Research Laboratories, Sumitomo Electric Industries  
1-1-1, Koya-kita, Itami, Hyogo 664, Japan

**PP3-12 PATTERN MARKING ON DIAMOND SURFACE BY PENNING DISCHARGE MICRO SPUTTERING**

Toshio Sugita, Eiichi Nishikawa, Yoshifumi Yoshida, and Shigeo Ebisawa  
Department of Electrical Engineering  
Science University of Tokyo  
Shinjuku-ku, Tokyo 162, Japan

**PP3-13 DIAMOND COATING OF SHEARING TOOLS USING BURNING GAS FLAME**

M. Murakawa, S. Takeuchi, and Y. Hirose  
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4-1 Gakendai, Miyashoro-Machi, Saitama-ken, Japan

**PP3-14 THE EFFECT OF THE TYPE AND AMOUNT OF THE GRAIN BOUNDARY PHASE IN S-TYPE POLYCRYSTALLINE DIAMOND ON ITS PHYSICAL PROPERTIES**

Yu Hongchang and Li Shangjie  
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No. 121 Huashan Road  
Zhengzhou, Henan, China

**PP3-15 TOUGH CRYSTAL OF CUBIC BORON NITRIDE**

Eiichi Iizuka  
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1 Soga, Shiojiri, Nagano-ken 399-64 Japan

**PP3-16 CUTTING PERFORMANCE OF C-BN BASED COMPACT MATERIAL BONDED WITH TiN- $\text{Al}_2\text{O}_3$  AND TiC- $\text{Al}_2\text{O}_3$**

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Kazuo Yamamoto  
Gifu Plant, Mitsubishi Metal Corp.  
Godo-cho, Anpachi-gun, Gifu-ken 503-23, Japan

**PP3-17 A STUDY ON THE OXIDATION RESISTANCE OF SINTERED DIAMOND POLYCRYSTALS WITH ADDITIVES**

Wang Dexin, Xue Yongjin, Jiao Qingyu, and Liu Peiluan  
Drilling Technology Research Institute of Sheng Li Oil Field  
Shan Dong, China

**PP3-18 DYNAMICS OF  $S_2$  AND  $S_3$  LUMINESCENCE IN DIAMOND**

Estela Pereira and Lucilia Santos  
Departamento e Centro de Fisica (INIC)  
Universidade de Aveiro  
3800 Aveiro Portugal

**PP3-19 THERMAL STABILITY OF DIAMOND FILMS**

Tatsuo Obata and Shingo Morimoto  
Omachi Research Laboratory, Showa Denko K.K.  
Omachi 6850, Omachi-shi, Nagano-ken 398, Japan

**PP3-20 RAMAN SPECTRA OF DIAMONDLIKE AMORPHOUS CARBON FILMS**

M. Yoshikawa, N. Nagai, G. Katagiri, H. Ishida, and A. Ishitani  
Toray Research Center, Inc.  
Otsu, Shiga 520, Japan

**PP3-21 DETECTION OF THERMAL DIFFUSIVITY FOR THIN SAMPLES AND POWDER WITH MICROPHONE-PHOTOACOUSTIC SPECTROSCOPY**

Qian Mengle and Wu Tatong  
Institute of Acoustics, Tongji University

Hou Li, Yang Peichun, and Qi Lichang  
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**PP3-22 LASER FLASH METHOD FOR INVESTIGATING THE THERMAL DIFFUSIVITIES OF THIN FILMS**

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**PP3-23 HIGH PERFORMANCE ELECTROFORMED DIAMOND CUTTING BLADES**

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**PP3-24 CERAMIC COATING ON DIAMOND GRAINS AND ITS APPLICATION TO GRINDING WHEELS**

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**PP3-26 THERMAL CONDUCTIVITY OF SYNTHETIC DIAMOND FILMS**

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## Appendix C

### BOOKS DESCRIBING DIAMOND TECHNOLOGY AND RESEARCH IN JAPAN

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**Chapter 2 History of the Diamond Vapor Phase Synthesis Method**

Nobuo Inuzuka, Aoyama Gakuin University

**Chapter 3 Mechanism of the Diamond Vapor Phase Synthesis Method**

**Section 1 Mechanism of Diamond Structure Formation by Vapor Phase Synthesis**

Minoru Sawada, Chiba University

**Section 2 Mechanism of the Vapor Phase and Surface Reaction in Diamond Film Formation**

Ikuhide Tachibana, Kyoto Institute of Technology

**Section 3 Mechanism of the Diamond Formation From the View of Plasma Diagnostics**

Osamu Matsumoto, Aoyama Gakuin University

**Chapter 4 Production Technology of Diamond Films**

**Section 1 Filament Method**

Ikuo Shibuki, Toshiba Tungaloy Company, Ltd.

**Section 2 Electron Impact Chemical Vapor Deposition**

Atsuji Sawanabe, Aoyama Gakuin University

**Section 3 Plasma Chemical Vapor Deposition**

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  - Section 1 Patent Application Trends of the Diamond Synthesis Method  
Akira Hosomi, Tomei Diamond Kogyo
  - Section 2 Market Prediction of Diamond Film Industry  
Ikuo Tomita, MITI

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# TURBULENT FLOW SIMULATION RESEARCH IN JAPAN

H. Yoshihara

**T**wo topics of turbulence research in progress at the University of Tokyo Institute of Industrial Science are described: (1) the derivation of higher order turbulence models using a statistical approach and (2) the calculation of a channel flow using direct and large eddy simulations. The matter of using mathematically incorrect periodic inflow/outflow boundary conditions in the channel flow is discussed.

## INTRODUCTION

A key tool for the design of advanced aerospace vehicles as advanced fighters and hypersonic aerospaceplanes is the Reynolds-averaged Navier/Stokes (R-A N/S) method using a mixing length turbulence model. In the relevant high Reynolds number range, it has yielded viable solutions over a wide class of problems. The R-A N/S method has, however, well-known shortcomings preventing its use in important problems. These shortcomings involve not only the turbulence model but the Reynolds-averaging process itself.

Consider the turbulence model. In many applications simple algebraic models such as the Baldwin/Lomax or the Cebeci/Smith model have sufficed, but there are important problems for which they are no longer applicable. One such problem arises when boundary layers from different origins come together as the merging of the fuselage boundary layer with the wing boundary layer. Another example is the confluent boundary layer on a multi-element airfoil

where the wake from the main airfoil mixes with the boundary layer on the downstream flap. In these cases there is no simple way to define the mixing length.

Another class of flows for which the local algebraic turbulence model falls short is the case of strong shock wave/boundary layer interaction where boundary layer separation occurs downstream of the shock. Here the instantaneous (equilibrium) adjustment of the eddy viscosity to the pressure gradient is too severe. A nonequilibrium model must be used where the finite rate of production, dissipation, and diffusion of the turbulence must be taken into account.

There has been considerable research on nonequilibrium turbulence models, including Bradshaw's one-equation model based on the turbulent energy equation and the widely used two-equation k-e model developed by Jones and Launder. In principle the use of the higher order equations should yield improved results, but in the above problems no significant improvements have been achieved. Failings here must be attributed to the inadequate evaluation of the parameters arising in the models. There are isolated exceptions as Johnson's model (Ref 1) for the case of shock-induced separation on an airfoil where excellent test/theory agreements were achieved. Johnson's model was obtained by averaging Bradshaw's turbulent energy equation across the boundary layer resulting in a first order ordinary differential equation in the streamwise direction for the eddy viscosity.

There are two directions for improving the turbulence modeling. The first is the familiar one of increasing the number of equations by taking "higher moments" of the Navier/Stokes equations. The rationale here is that by applying closure assumptions on higher moments, more exact modeling will be achieved. Such a route will lead to greatly increased computing, but improved results have not followed. This leads to the second and more preferable route for improving the turbulence model, namely, starting with a minimal number of modeling differential equations and improving the quality of the model parameters. This approach is being followed by Professor Yoshizawa and his colleagues at the University of Tokyo Institute of Industrial Science.

There are well-known fluid dynamic problems for which the Reynolds averaging cannot be used. Such a case is the turbulent diffusion flame as in an aerospaceplane scramjet engine where the key mechanism for the combustion process is destroyed by the averaging. In a hydrogen/oxygen diffusion flame a jet of hydrogen issues into an ambient flow containing oxygen. The reaction rate in such a flame is determined not by the chemical reaction rates but by how fast the reactants are brought together. That is, the reaction rate is diffusion-limited with the diffusion process dominated by the turbulent intermittency at the jet boundary. Here a Reynolds-averaging blurs the intermittency, the key mixing mechanism.

Another class of flows where Reynolds-averaging must be abandoned for different reasons is the case of hypersonic turbulence and laminar/turbulent transition. Here the fluctuation velocities are supersonic, and the turbulence becomes

compressible. In this case the R-A N/S equations contain, besides the Reynolds stress terms, terms with density and pressure fluctuations. The great difficulty in obtaining experimental data to model the latter terms discourages the use of the R-A N/S equations.

Direct simulation and large eddy simulation (LES) are recent approaches for resolving the above difficulties. Here turbulent flow is viewed as a highly unsteady laminar flow. In the case of direct simulation, the unsteady (laminar) Navier/Stokes equations are solved directly using a highly refined mesh and a small time step to resolve the important turbulence scales. Because of computer resource limitations, these calculations have been restricted to unrealistically low Reynolds numbers where even the maintenance of turbulence is marginal. To ease this problem, in LES calculations the smaller scales of turbulence requiring the highly refined mesh are filtered out by averaging the local fluctuation with the neighbors using a sharp drop-off weighting function. With the high frequency/short wavelength fluctuations removed, a coarser mesh and a larger time step can be used leading to a reduced computer resource requirement. This significant reduction of the problem size is, however, obtained at the heavy cost of needing a closure for the filtered flow that must mimic the effects of the eliminated turbulence scales on the retained scales.

In Japan there are important contributions being made to the fundamental problems described above. In the following, the statistical turbulence modeling and LES research being conducted at the University of Tokyo Institute of Industrial Science (IIS) are described.

## FUNDAMENTAL TURBULENCE STUDIES AT IIS

The staff of IIS is organized into laboratories, each headed by a senior professor. Typically a laboratory is staffed by the professor in charge, several senior colleagues, and several assistants or graduate students. The Numerical Simulation for Turbulence (NST) Research Group at IIS is composed of three laboratories: the Kobayashi Laboratory, the Murakami Laboratory, and the Yoshizawa Laboratory. Fundamental turbulence studies are conducted in Professor Akira Yoshizawa's laboratory, while basic and applied calculations are undertaken in the Kobayashi and Murakami Laboratories. The NST Group holds monthly coordination meetings and sponsors a Japan-wide symposium on turbulence research each February with the fourth symposium scheduled in 1989.

In the following sections the fundamental turbulence research conducted in the Yoshizawa Laboratory is described, in particular the statistical modeling of turbulence by Professor Yoshizawa and the extensive LES computations of the channel flow by Dr. Kiyoshi Horiuchi.

### Statistical Modeling of Turbulence

Turbulent flow is characterized by continuous "space/time" spectra ranging from macroscopic scales characteristic of the problem on hand to the Kolmogorov dissipation scales. Typically energy cascades downward from the macroscopic to the Kolmogorov scales via the intermediate scales. In the Kraichnan Direct Interaction (DI) model (Ref 2), the starting point for Professor Yoshizawa's statistical approach, turbulence is separated into a mean flow

and a fluctuating flow, these two flows having widely separated scales that interact directly without an intermediate cascading.

Professor Yoshizawa's purpose in developing a statistical turbulent theory with the incompressible Navier/Stokes equations is not for the prediction of turbulent flows but for evolving improved turbulent transport models. The DI method developed by Kraichnan is highly formal and is not readily usable. Professor Yoshizawa's contribution is in the simplification of the Kraichnan theory through the introduction of a multiscale expansion (iterative) procedure (Ref 3).

In the two-scale DI theory, the velocity vector  $u$  and the pressure  $p$  are separated into the mean (ensemble average) component  $(U, P)$  and the fluctuating component  $(u', p')$ ; that is,

$$f(u, p) = F(U, P) + f'(u', p')$$

where

$$u = u(x, t) \quad p = p(x, t)$$

$$U = U(X, T) \quad P = P(X, T)$$

$$u' = u'(x, t; X, T) \quad p' = p'(x, t; X, T)$$

Here  $(X, T)$  and  $(x, t)$  are the space vector and time scales for the mean and fluctuating components of the flow, respectively, and  $X = O(\delta x)$  and  $T = O(\delta t)$ , where  $O$  = order and  $\delta$  is a scaling parameter  $\delta \ll 1$ . In  $u'$  and  $p'$ , the arguments  $(X, T)$  essentially serve as parameters.

With the above hypothesis, the incompressible Navier/Stokes equations are separated in the familiar fashion into a set of mean flow equations containing the "eddy" shear terms and the set of fluctuation equations.

To evolve a usable form, the fluctuation equations are first transformed using a Fourier transform in the fluctuation space vector  $x$ . The solution in the transform space is then postulated in terms of a power series in  $\delta$  given by

$$f(k, X; t, T) = \sum_{n=0}^{\infty} \delta^n f_n(k, X; t, T) \quad (1)$$

where  $f$  is the "convected" transform of  $f'(x, t; X, T)$ .

Using the resulting expression for  $f$  and choosing  $u'_0$  (in  $f_0$ ) to be isotropic, the eddy shear terms in the mean flow equations can be expressed in terms of the "isotropic covariance"  $Q$  of  $u'_0$ , and the corresponding isotropic solenoidal and nonsolenoidal mean "response functions"  $F$  and  $G$ . The argument for these functions is  $(k, t, t'; X, T)$ .

Taking moments of the fluctuation equations, equations for  $Q$ ,  $F$ , and  $G$  are obtained. These equations constitute the turbulence model. The complete system of turbulent flow equations is then composed of the mean flow equations with the eddy shear terms defined by the three-equation turbulence model.

The first use of these equations was for the derivation of a higher order anisotropic eddy viscosity model (Ref 4) to resolve the difficulty of isotropic models that required a zero shear for zero rate of strain. Nishijima and Yoshizawa (Ref 5), using the anisotropic eddy viscosity together with the standard  $k$ - $\epsilon$  method, calculated a channel flow and a Couette flow. In the latter, the anisotropy of the turbulence was reasonably predicted.

Using the above approach, Professor Yoshizawa further obtained:

1. A higher order turbulent energy equation (Ref 3) and dissipation rate equation (Ref 6)
2. A higher order Smagorinsky subgrid model for the LES equations (Ref 7)
3. An LES subgrid model for the compressible case (Ref 8)

In the above cases, the modeling was guided by existing base models, and the results obtained then suggested the format for higher order transport models. Though the limiting case of small compressibility was considered, the results of Reference 8 could suggest the structure for the pressure and density fluctuation transport terms needed for the hypersonic case.

### LES Calculations of the Channel Flow

In a direct simulation, turbulent flow is considered a highly unsteady laminar flow and calculated using the unsteady Navier/Stokes equations. This deterministic approach for the turbulent flow will then mandate that all rules pertaining to the formulation of the initial/boundary conditions for such problems be followed. Thus, for example, in the case of a channel flow, this will require the fluctuating inflow conditions on all of the dependent variables to be prescribed at the upstream boundary and a simple outflow condition prescribed at the downstream boundary. In the hypersonic laminar/turbulent transitional flow over a cone in a wind tunnel, not only must the inflow free stream turbulence be prescribed but the noise from the wind tunnel walls must be prescribed as well. The need for these difficult boundary conditions in a strict formulation of the problem would greatly discourage use of direct simulation.

Another difficulty, though a temporary one, is that the computer resource requirements to carry out direct simulation calculation with adequate space/time resolution are significantly larger than can be accommodated by existing supercomputers. Rogallo and Moin (Ref 9) suggested that for a channel flow the number of mesh points required was approximately  $(6 Re_m)^{3/4}$ , where  $Re_m$  is the channel Reynolds number. That is, for  $Re_m = 10^4$ , approximately  $5 \times 10^{10}$  mesh points would be required with 2,000 time steps needed to attain a statistically steady flow.

LES is an approach to reduce the computer resource requirements to a more manageable level. Here the high frequency fluctuation components are filtered out by an averaging process in which the fluctuating quantity at a given point is averaged with the neighbors with a sharp-dropoff weighting function such as a narrow Gaussian. If such a redefinition of the dependent variables is introduced into the incompressible Navier/Stokes equations, a filtering (eddy) shear term will arise in the filtered equations which must be modeled. The eddy shear term is divided into three parts: the Leonard term, cross term, and the Reynolds stress term. The usual procedure is to treat the Leonard term explicitly, set the cross term to zero, and use the algebraic Smagorinsky model for the Reynolds stress term. In the latter term, a van Driest-type damping is required. The above approximation of the eddy shear terms loses Galilean invariance. Bardina (see Ref 10) suggested an alternate approximation of the cross term and the Reynolds shear term that recovered the Galilean invariance.

In the following, calculations of the channel flow by Dr. Horiuchi (Ref 10) are described. The channel considered has a

height  $H$  (z-axis), a spanwise width  $1.6H$  (y-axis), and a streamwise length  $3.2H$ . The channel flow was assumed to be statistically homogeneous in both the spanwise and streamwise directions. The spanwise and streamwise dimensions of the channel were selected to be significantly greater than the empirical two-point correlation distance. Periodic boundary conditions in the spanwise and streamwise directions were then assumed. For the solution, Fourier expansions in the x and y directions were used, and a finite difference method was used in the nonhomogeneous z direction to determine the Fourier coefficients.

Direct simulation and LES calculations for the channel flow were carried out side-by-side in time. The channel Reynolds number was 360 based on the shear velocity and the channel height. For the direct simulation calculations the mesh dimensions were  $128 \times 256 \times 129$ , whereas for the LES calculations the mesh dimensions were  $32 \times 64 \times 129$ . (In both calculations, Fourier series in the x and y directions were used.) In the LES calculations, Gaussian filters were used in the streamwise and lateral directions. The filtered velocity field from the direct simulation was used as the initial flow for the LES calculations. Inflow conditions were the same in the direct simulation and LES calculations.

Calculations were carried out with the following eddy shear term models: (1) Leonard + Smagorinsky, (2) Leonard + Bardina, and (3) Smagorinsky only. Instantaneous correlations, the ratio of the rms values, and the ratio of the mean values between the filtered direct simulation and LES results were determined at points across the channel. The results indicated the following:

1. The Leonard term essentially canceled the Bardina cross term confirming that the explicit retention of the Leonard term alone and the neglect of the cross term would be significantly worse than retaining only the Smagorinsky term.
2. The correlation of the filter shear terms (Leonard + Bardina terms) between the filtered direct simulation and LES results showed a relatively high correlation, but the ratios of the rms and mean values were very poor (approximately 0.25-0.5) across the channel. That is, an improved filter shear model is needed.
3. The correlation of the streamwise fluctuations between the direct simulation and the LES result was approximately 0.75 across the channel, the same correlation found for the corresponding filter shear terms.

The above lack of agreement between the filtered direct simulation and LES results is primarily due to two causes. The first is an inadequacy of the Bardina model for the cross flow and Reynolds shear stresses, while the second is the worsening of the truncation errors in the LES solution.

It would be of interest to isolate these effects, for example, by removing the difference in the truncation errors using the same mesh for the direct simulation and LES calculations. Here it is essential to keep the filter invariant in the fine and coarse mesh calculations.

Finally, earlier calculations (Ref 11) and those of Moin and Kim (Ref 12), who used the same problem formulation, showed "turbulence" streaks with lateral spacing about 2-1/2 times larger than observed in experiments.

## CONCLUDING REMARKS

The two-scale Direct Interaction method developed by Professor Yoshizawa is an attractive route for acquiring higher order turbulence models. Of particular interest is the possible modeling of the Reynolds-averaged shear terms containing density and pressure fluctuations arising in hypersonic turbulent and transitional flows. Higher order turbulence models must be tuned and eventually validated by test/theory comparisons.

Comparison of the filtered direct simulation and LES solutions of the channel flow by Dr. Horiuchi showed the inadequacy of the Bardina model for the cross flow and Reynolds stresses. Improved models are needed for the filtered shear terms, but they probably must await a suitable modeling data base most probably to be generated by direct simulation calculations at the appropriate Reynolds numbers.

Direct simulation and LES formulations of the turbulence problem are mathematically fully deterministic so that established guidelines for prescribing initial and boundary conditions must be followed. Viable instantaneous flow predictions can be insured only if the appropriate inflow/outflow conditions are prescribed. In most channel flow calculations, however, periodic boundary conditions are used instead at the upstream/downstream boundaries. That is, the instantaneous velocities are assumed to be identical at corresponding points of the upstream and downstream boundaries. The rationale used is that if the channel is long enough, the flow at points located beyond the two-point correlation distance from either boundary will be independent of the inflow/outflow conditions. It would be of interest to verify this in a

direct simulation or LES calculation by prescribing two sets of inflow/outflow conditions and comparing the resulting instantaneous velocities at points midway between the upstream and downstream boundaries. Of particular interest would be to take inflow conditions with two lateral scales for the inflow fluctuations and compare the lateral spacing of the resulting turbulence streaks.

Direct simulation or LES solutions, because of their complexity, are difficult to assess. It is thus essential to have on hand appropriate experimental data.

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## REFERENCES

1. D. Johnson, "Predictions of transonic separated flow with an eddy-viscosity/Reynolds-shear-stress closure model," *ALAA J.* (December 1986).
2. R. Kraichnan, "Direct-interaction approximation for shear and thermally driven turbulence," *Physics of Fluids* 7, 1048-62 (1964).
3. A. Yoshizawa, "A statistically derived system of equations for turbulent shear flows," *Physics of Fluids* 28(1) (January 1985).
4. A. Yoshizawa, "Statistical analysis of the deviation of the Reynolds stress from its eddy-viscosity representation," *Physics of Fluids* 27(6) (June 1984).
5. S. Nishijima and A. Yoshizawa, "Turbulent channel and Couette flows using an anisotropic k-e model," *ALAA J.* 25(3) (March 1987).
6. A. Yoshizawa, "Statistical modeling of a transport equation for the kinetic energy dissipation," *Physics of Fluids* 30(3) (March 1987).
7. A. Yoshizawa, "A statistically-derived subgrid model for the large-eddy simulation of turbulence," *Physics of Fluids* 25(9) (September 1982).
8. A. Yoshizawa, "Statistical theory for compressible turbulent shear flows, with the application to subgrid modeling," *Physics of Fluids* 29(7) (July 1986).
9. R. Rogallo and P. Moin, "Numerical simulation of turbulent flows," *Annual Review of Fluid Dynamics* 16, 99-137 (1984).
10. K. Horiuchi, The role of the Bardina model in large eddy simulation of turbulent channel flow, Preliminary Report (University of Tokyo Institute of Industrial Science, 1988).
11. K. Horiuchi, "Comparison of conservative and rotational forms in large eddy simulation of turbulent channel flow," *J. of Comp. Phys.* 71(2) (August 1987).
12. P. Moin and J. Kim, "Numerical investigation of turbulent channel flow," *J. Fluid Mech.* 118, 341-77 (1982).



*Hideo Yoshihara arrived in Tokyo in April 1988 for a 2-year assignment as a liaison scientist for the Office of Naval Research. His assignment is to follow the progress of advanced supercomputers and to review and assess the viscous flow simulation research in the Far East. Dr. Yoshihara formerly was with the Boeing Company, where he was Engineering Manager for Applied Computational Aerodynamics. He was also an affiliate professor in the Department of Aeronautics and Astronautics of the University of Washington, an ALAA Fellow, and a former member of the Fluid Dynamics Panel of AGARD/NATO.*

# TEXTURING OF MAGNETIC RECORDING DISKS BY ANODIC OXIDATION

Noboru Tsuya, Tadao Tokushima, Makoto Shiraki, and Earl Callen

**I**n both perpendicular and magnetic recording one wants to have the flying height of the magnetic head as low as possible. Heads are now set at about  $0.25\text{ }\mu\text{m}$  to avoid hitting protrusions in the disk surface. The source of these protrusions is mechanical texturing. Disks must be slightly bumpy or the head sticks to the flat surface. Disks are customarily scored with emery tape to roughen the surface. This produces an irregular texturing, with high points that hit the head. A new and better way of texturing is by a chemical and electrolytic process. Micropores are etched into an alumina film anodically oxidized onto the aluminum disk substrate. The pores are filled either with a magnetic core, iron, for perpendicular recording disks or a nonmagnetic core, perhaps copper, for longitudinal recording disks. After polishing, the alumina is etched away to expose about  $200\text{-}\text{\AA}$  metal studs. These texture the surface so uniformly that magnetic heads can be flown as low as  $0.1\text{ }\mu\text{m}$ .

## INTRODUCTION

In an earlier *Scientific Bulletin* we described a unique approach to perpendicular magnetic recording (Ref 1). The magnetization is forced to lie perpendicular to the disk plane by the demagnetization field. Aluminum disk blanks are electrolyzed in a bath containing a mild acid. Anodization forms an alumina ( $\text{Al}_2\text{O}_3$ ) layer and the acid simultaneously etches

long cylindrical micropores perpendicular to the surface. The pores are arrayed in a lovely, two-dimensional hexagonal close-packed (honeycomb) lattice, illustrated in Figure 1. (A nice physics problem, so far unaddressed, is how nature breaks symmetry in this particular way.) To make a perpendicular magnetic recording disk iron is electrodeposited in the pores (Ref 2).

Something of the same kind of trick, but for a different purpose, turns out to work admirably to solve another problem, and in this addendum we describe the new process.

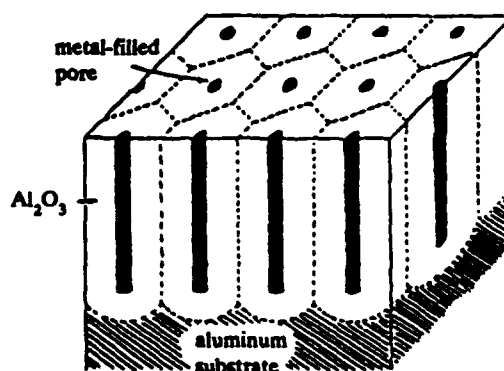


Figure 1. Honeycomb of pores in the oxide layer. The pore diameter is actually much closer to the cell size than is shown in the drawing. See Figure 4.

## WHY

In magnetic recording it is necessary that the flying height of the magnetic head above the disk remain constant throughout each individual revolution, and so the rigid disk must be accurately flat. For maximum

signal and high packing density one wishes the lowest possible flying height. But at low flying height the head collides with the smooth, flat surface of the disk. This is a universal problem and it is exacerbated by a humid atmosphere. The usual method of dealing with it is to abrade ("texture") the surface. Emery tape is held against the rotating disk, scoring it with rough, longitudinal and more-or-less parallel grooves. The detritus must be removed in its entirety.

Figure 2 is a scanning tunneling electron microscope (STM) image of a sputtered disk so textured. The average peak-to-valley distance is about 200 Å, but the ridges are not of uniform height--some peaks are twice that height. To avoid hitting irregular peaks it is necessary to operate at a flying height of 0.2 to 0.25 μm, for bumping of the magnetic head into high points creates noise and damages the head.

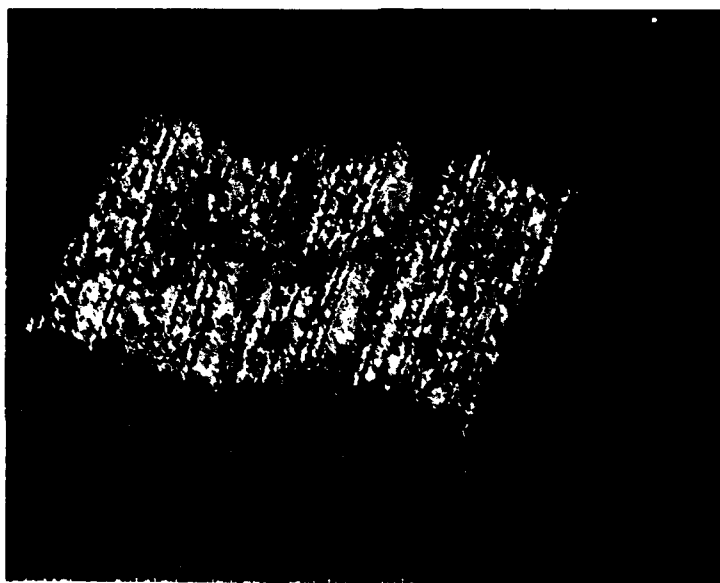


Figure 2. Scanning tunneling microscope image of the surface of a disk mechanically textured by scoring with emery tape. Dimensions are in Angstroms.

## PERPENDICULAR RECORDING DISKS BY CHEMICAL TEXTURING

There is a better way of texturing, a little more complicated to make but producing a superior product. For the moment let us think of making a perpendicular magnetic recording disk (Ref 3). The same principle can be applied to longitudinal recording, and we shall discuss that later. The starting point (see Figure 3) is the usual

Al (alloy) substrate. The disk is connected anodically and oxidized in a 3 wt. % oxalic acid bath until a 3- to 7-μm alumina ( $\text{Al}_2\text{O}_3$ ) film is formed. As described in Reference 1, in the acid bath oxidation, cylindrical micropores are etched in the alumina film as it grows. The distance between micropores is determined by the electrolysis voltage; a typical separation is about 1,000 Å. After some intermediate steps iron is electrodeposited in the pores.

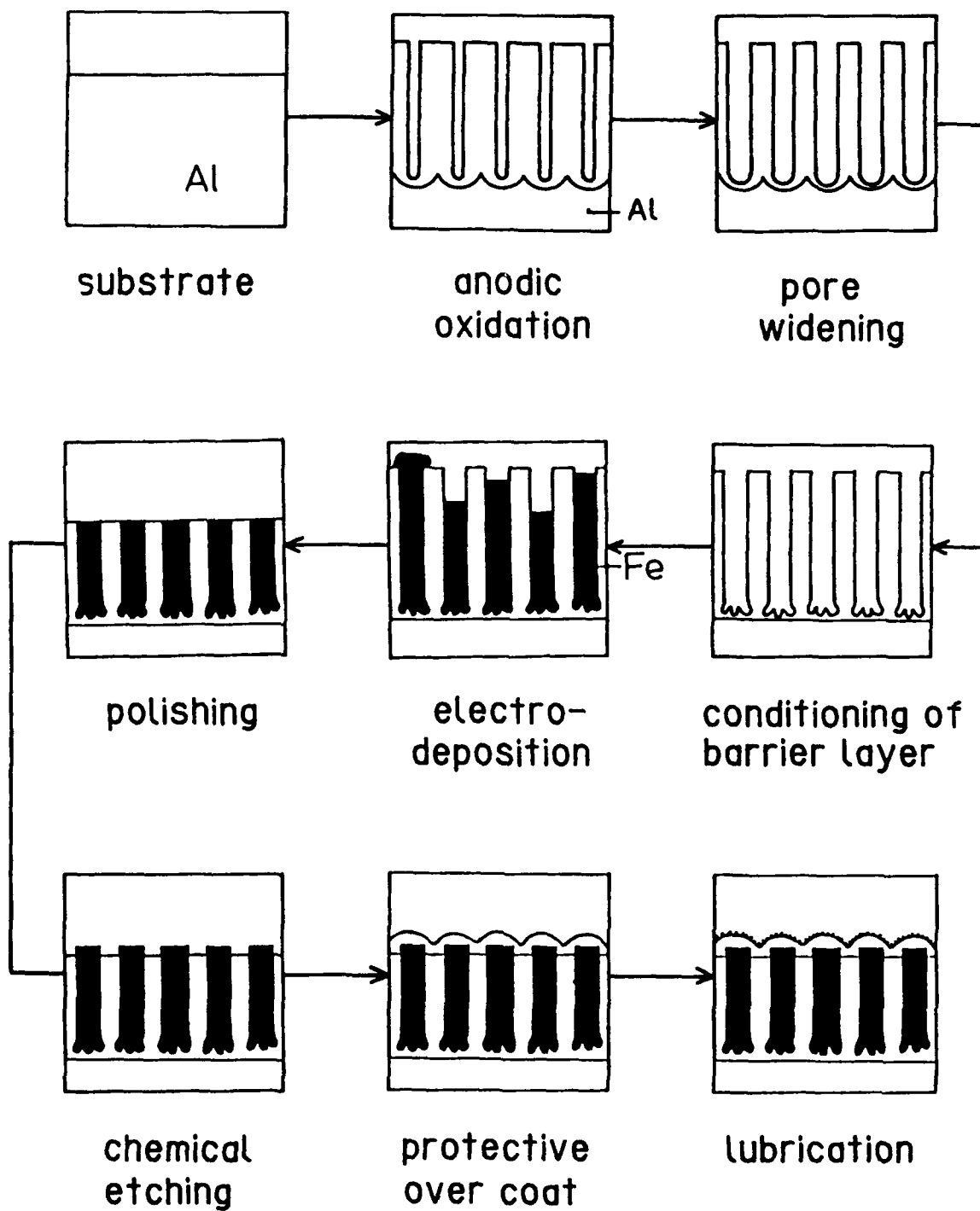
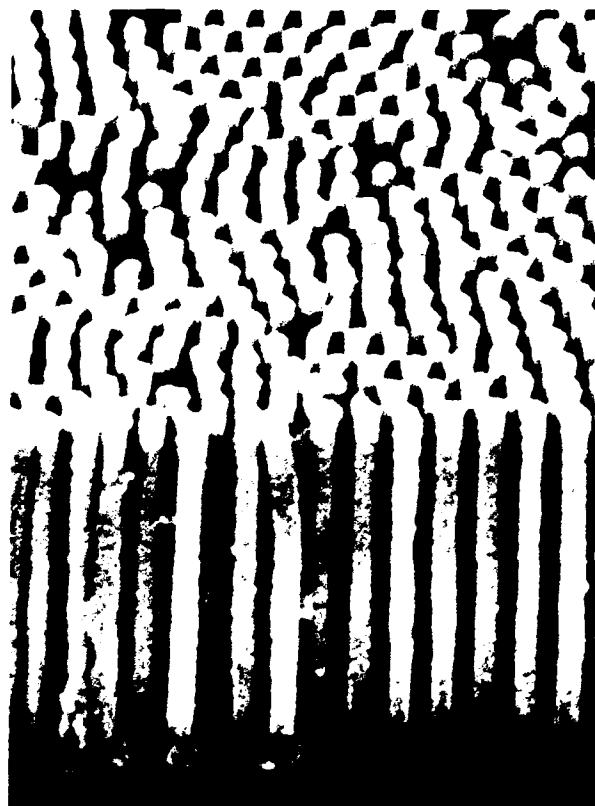


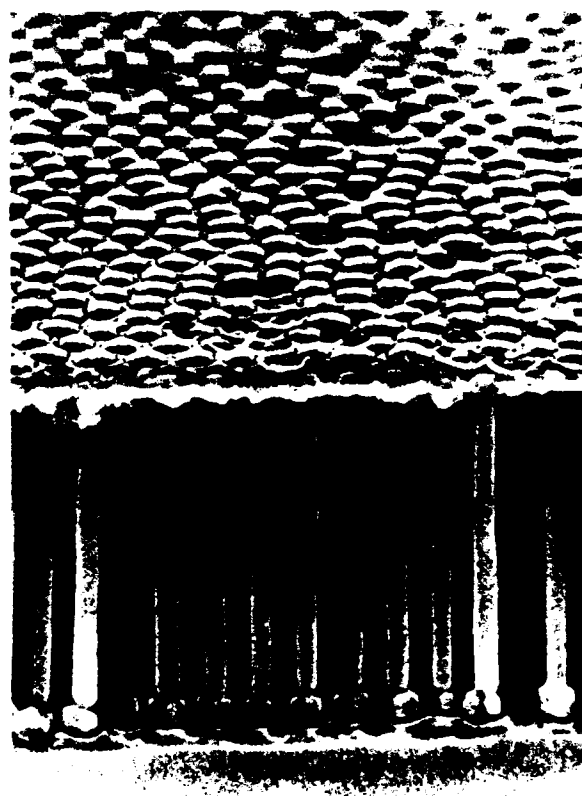
Figure 3. Schematic of steps in the preparation of a perpendicular recording disk by anodic oxidation and pore filling.

The disk is polished flat and then immersed in an acid bath (a mixture of phosphoric and chromic acid). The acid etches away the alumina but leaves the iron needles intact. In this way about 200-Å-high metal studs are exposed above the alumina. A thin lubricating graphite coating is next deposited and finally a monolayer, about 40 Å, of an oil lubricant (perfluoropolyether) is sprayed on. Surprisingly, endurance tests suggest that the oil layer should remain intact for as long as 5 years. To estimate oil retention, disks--held at a temperature of 80 °C but under otherwise normal operating conditions--have been spun at normal operating speed, 3,600 rpm, for

up to 20 days with no increase in friction and no evidence of oil loss. Figure 4 shows scanning electron microscope (SEM) micrographs of the cross section of the chemically textured disk before and after deposition of the carbon layer. Surfaces are unusually smooth.  $R_z$ , the long wavelength (one micron scale) rms deviation from flatness, is about 10 Å after polishing and is the same after etching. (On the micron scale the studs add very little.) The carbon deposition, which is a bit irregular, increases  $R_z$  to something less than 20 Å. Figure 5, obtained by laser interferometry, compares surface roughness profiles of disks prepared by the two methods.

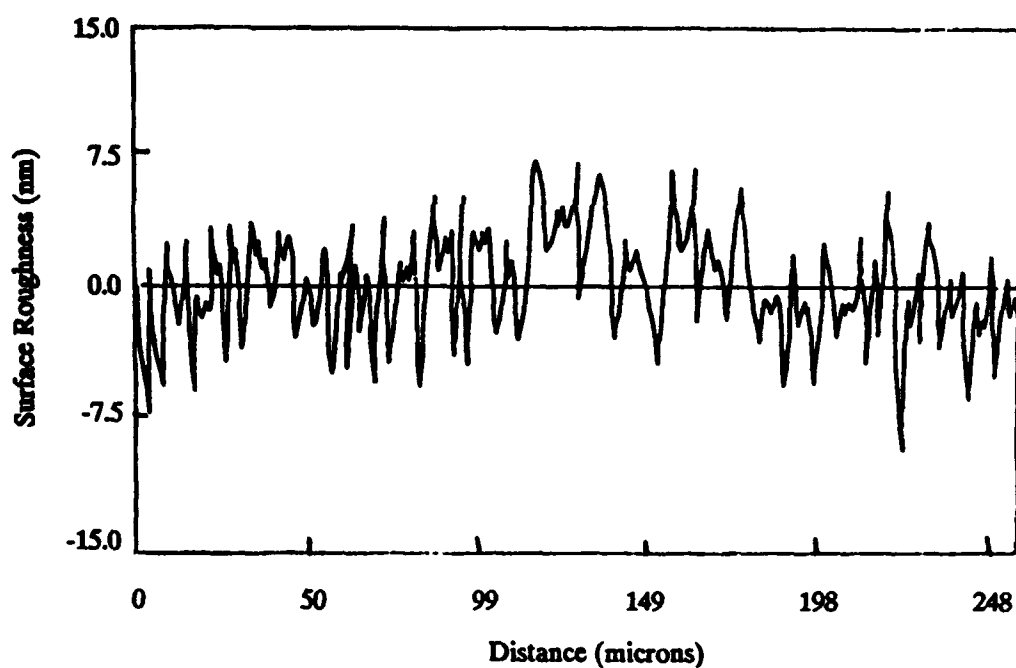


(a) After chemical etching and before carbon coating.

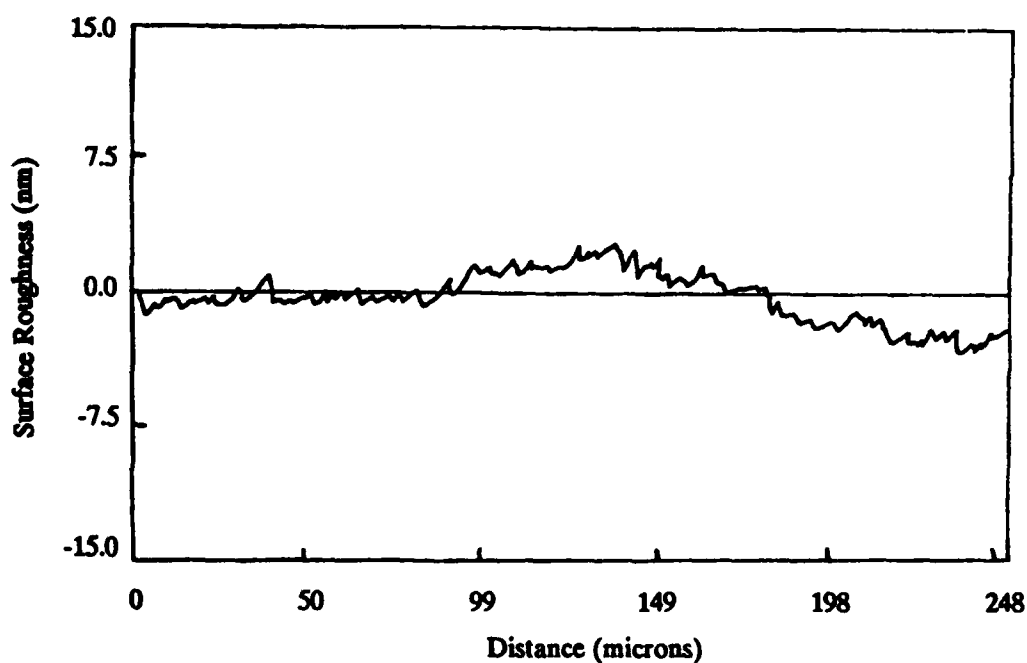


(b) After graphite coating.

Figure 4. Scanning electron microscope images of the cross section of a chemically textured perpendicular magnetic recording disk.



(a) Mechanically scored disk.



(b) Anodic-oxidized, chemically textured perpendicular magnetic recording disk.

Figure 5. Comparison of surface roughness profiles. Profiles are measured by laser interferometry.

The liquid lubricant not only reduces initial friction but is essential in maintaining the long-term smoothness of the disk. Figure 6 demonstrates this. The figure shows the coefficient of friction as a function of the number of passes--the number of times a ferrite head with a 15-g load was run over the disk, at 25 cm/s speed.

Without any etching (0 Å), the coefficient of friction exceeds 1.2. Minimum friction occurs at 200- or 300-Å stud protrusion, but with usage the surface wears and degrades to the unetched value. However, with the monolayer liquid lubricant there is no observable increase in surface mechanical friction after 1,500 passes of the head over the same track.

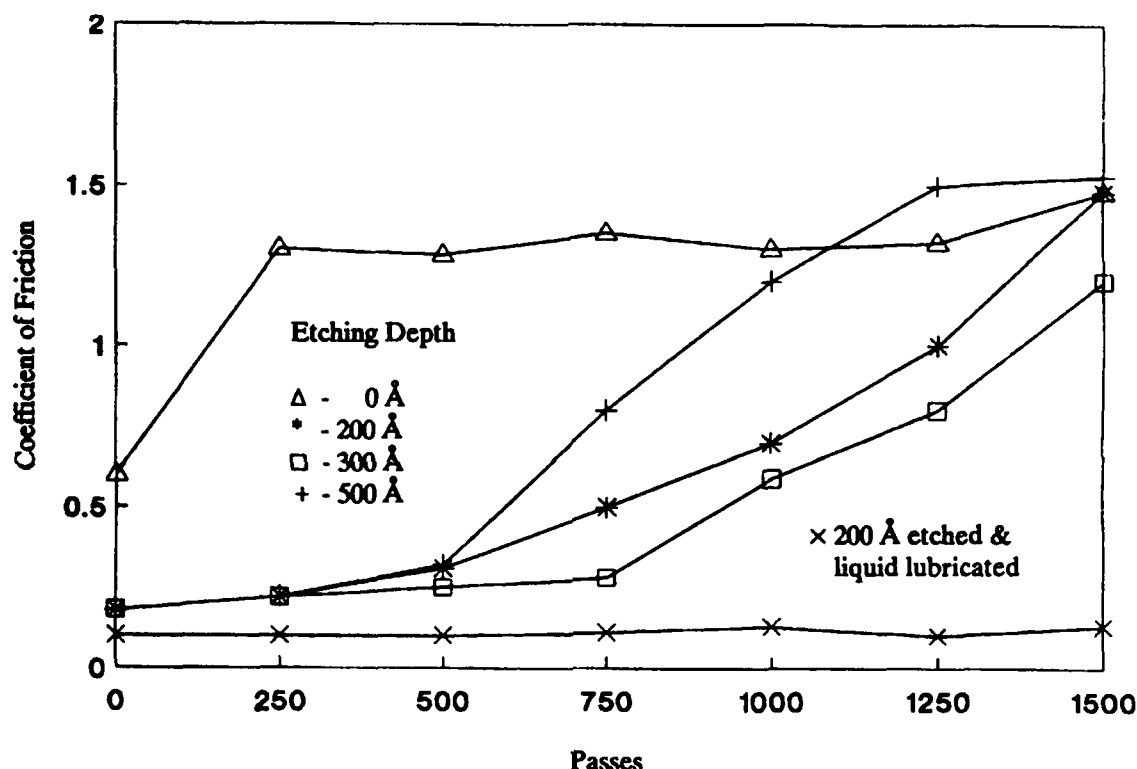


Figure 6. Endurance tests of anodic-oxidized disks. The figure shows the coefficient of friction versus number of passes of a Mn-Zn ferrite head, loaded to 15 g. The relative speed of head and disk was 25 cm/s. The disks were all overcoated with carbon. Curves in the figure represent disks etched to various depths (or heights of protrusion of the iron studs). Without the liquid lubricant, after many passes all disks revert to the coefficient of friction of the unetched disk. With the lubricant oil, after 1,500 passes the 200-Å etched disk shows no evidence of erosion or of increased friction.

## LONGITUDINAL RECORDING SPUTTERED RIGID DISKS

In making perpendicular recording disks by anodic oxidation, etching for texturing is a natural extension since the partially projecting magnetic needles can serve both purposes. In making sputtered longitudinal recording disks, etching and filling micropores and exposing studs introduce additional steps in the manufacturing process. Nevertheless, the chemically textured disks seem to be worth the trouble. The process is depicted in Figure 7. By electrodeposition the micropores in the alumina layer are in this case filled with a nonmagnetic metal--Cu or Sn. (Cu seems to work better as Sn has a tendency to swell up and bulge when the disk becomes heated in later deposition steps.) The surface is polished to a thickness of 2 to 5  $\mu\text{m}$ , until smooth and flat, and the alumina is etched away some 200  $\text{\AA}$  to expose the texturing studs. On top of this, layers of Cr ( $\sim 1,000 \text{ \AA}$ ), CoNiCr ( $\sim 600 \text{ \AA}$ ), and finally graphite ( $\sim 300 \text{ \AA}$ ) are deposited by sputtering. Figure 8 is an STM image of the final product. Figure 9, an SEM micrograph of the surface at a tilt angle of  $70^\circ$ , shows the regularity of the graphite and metal-coated studs. In Figure 10 we compare curves of rms voltage picked up by a piezoelectric sensor versus disk velocity, recorded on disks prepared by the two methods. Collisions of the sensor with the disk cause twice the noise voltage in the mechanically textured disk. To reduce irregularities mechanically textured disks are burnished; a hard cutter is run low above the disk to knock off high points. So far it is not entirely effective. The metal protrusions seem to bend, and sometimes the surface is damaged. But no doubt it will be possible to smooth the mechanically textured disks.

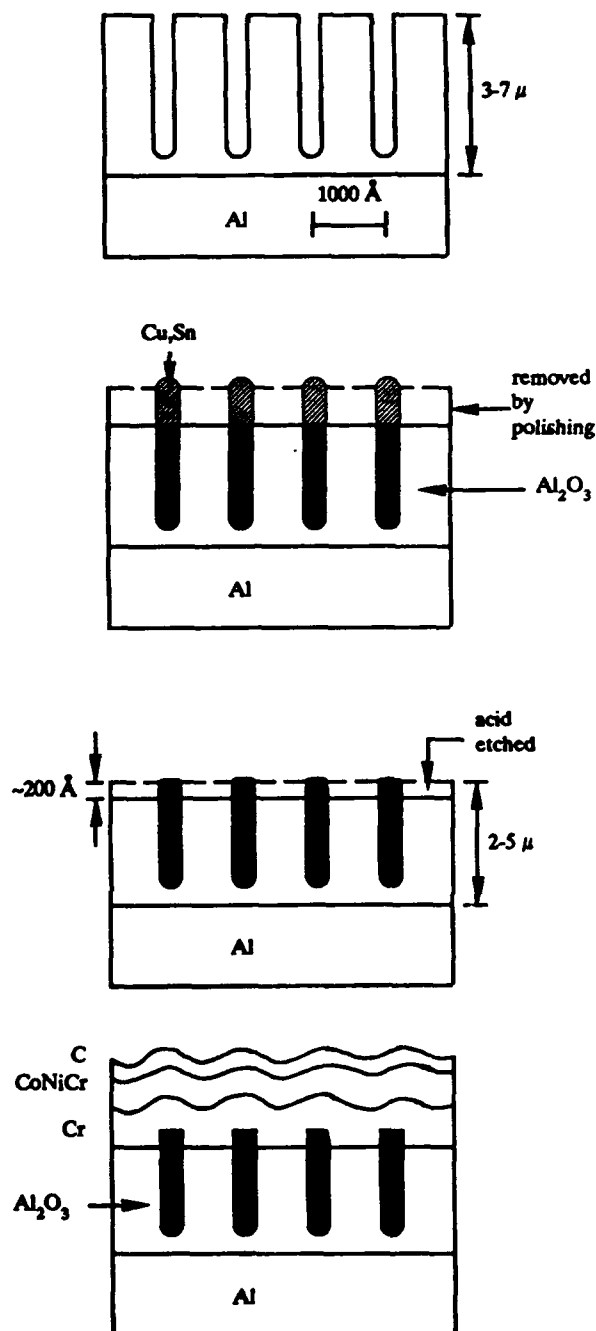


Figure 7. Schematic of preparation of longitudinal recording disk. Pores are etched and filled with Cu or Sn or some nonmagnetic metal. After polishing the surface very smooth the  $\text{Al}_2\text{O}_3$  is etched away to expose the metal studs. This is coated with Cr, the longitudinal recording magnetic layer (CoNiCr), the protective carbon overlayer, and finally a monolayer of oil.



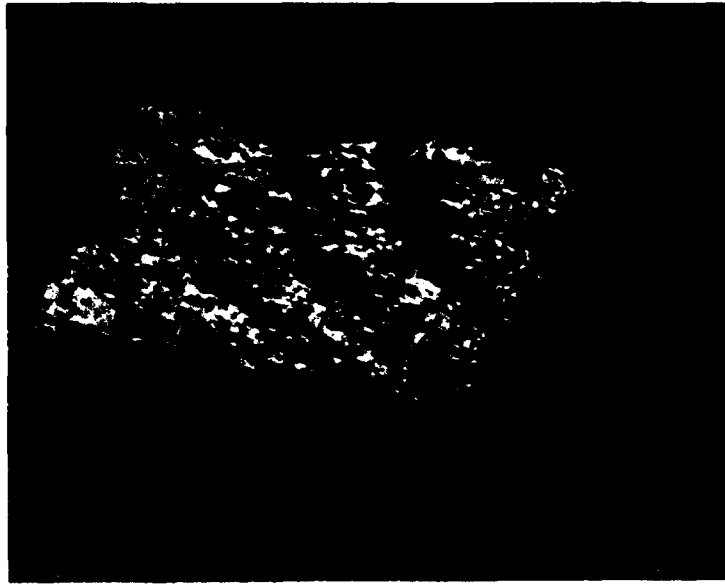


Figure 8. Scanning tunneling microscope image of the graphite-coated, studded, longitudinal recording disk. All distances are in Angstroms.

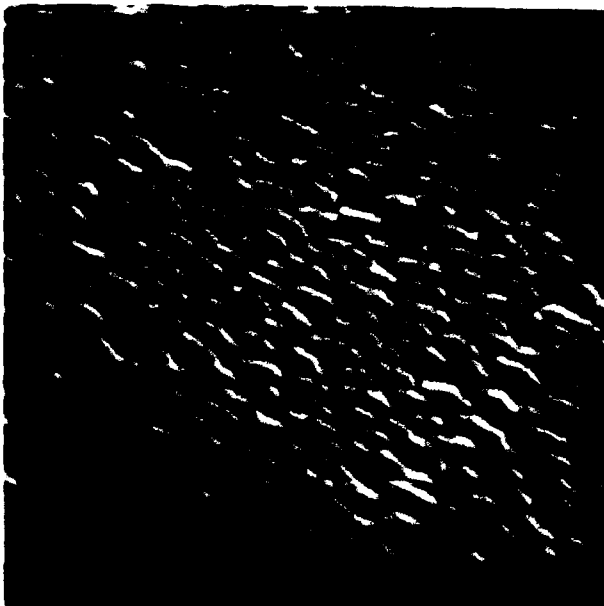


Figure 9. Scanning electron microscope image of the surface, at a tilt angle of 70°.

One advantage of mechanical texturing is in the B/H loop in longitudinal recording. The circumferential grooves along the track of the head improve the squareness of the loop and improve envelope modulation. (In perpendicular recording, because of the geometry the isotropy of the bumps in one case and the parallelism of the grooves in the other have no effect on the B/H loop.)

Certainly, if the push is toward perpendicular recording, this should be accompanied by reducing flying height. At higher flying height longitudinal recording produces a larger signal voltage than does perpendicular recording. Mechanically textured disks cannot be run at 0.1- $\mu\text{m}$  flying height and chemically textured disks can,

and that is what it is all about.\* Of course, when the chemically textured disk is run at half the height of the mechanically abraded disk it yields a higher bit density and better signal/noise, and this will hardly surprise anyone. At the present stage of magnetic recording technology and requirements, it seems easier to use longitudinal recording because no special circuitry for equalizing the waveform is needed in the longitudinal

case, as is required with perpendicular recording. And so there is a need right now for longitudinal recording disks that can operate at a flying height of 0.1 to 0.15  $\mu\text{m}$ . As higher bit density requirements push the technology in the future, perpendicular recording disks capable of tolerating a flying height of 0.1  $\mu\text{m}$  and less will be in demand.

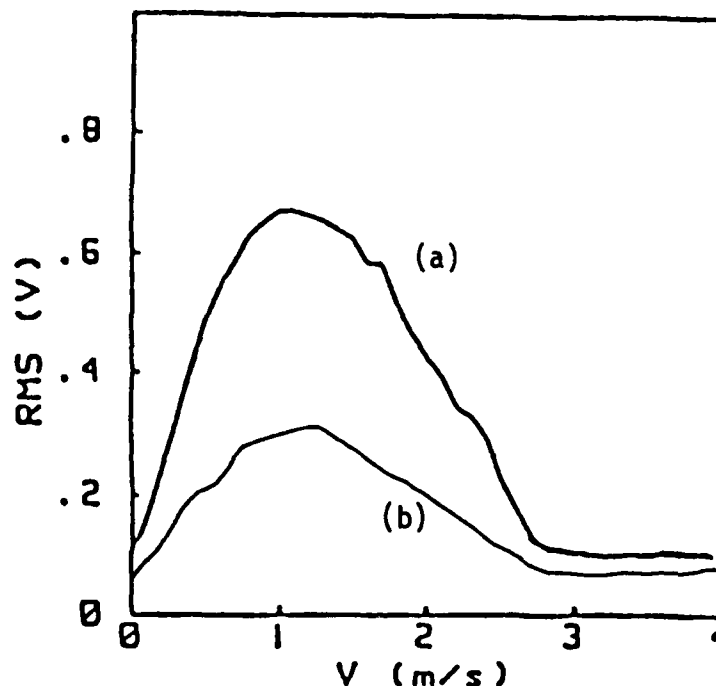


Figure 10. Output voltage of a piezoelectric sensor head versus velocity of (a) a mechanically textured (emery-scored) disk and (b) a chemically textured longitudinal disk. At low velocities and flying heights the head hits the mechanically scored disk, generating twice the noise signal in the piezoelectric head. At high velocities the head flies well above the disk.

\* We remind the reader that flying height is not a constant over the disk. The angular velocity of the disk is constant, and so the linear relative velocity of head and disk is proportional to the distance of the track from the center. As the head flies faster further out, it flies proportionally higher. But if the head is set to fly higher in the inner region in one case than in the other, it stays proportionally higher all the way out.

## REFERENCES

1. N. Tsuya, T. Tokushima, and E. Callen, "Perpendicular magnetic recording by anodic oxidation," *Scientific Bulletin* 12(3), 1 (1987).
2. N. Tsuya, T. Tokushima, M. Shiraki, Y. Wakui, H. Nakamura, and Y. Katsumata, *IEEE Trans. Mag.* MAG-23, 53 (1987); see Reference 1 for earlier references.
3. N. Tsuya, T. Tokushima, M. Shiraki, Y. Wakui, Y. Saito, H. Nakamura, and Y. Harada, Joint Intermag/M<sup>3</sup> Conference, Vancouver, B.C., June 1988. Conf. Proc. to appear in *IEEE Trans.*

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# INTERNATIONAL CONFERENCE ON SURFACE ENGINEERING

F.S. Pettit and E. Chen

**S**urface engineering currently encompasses a very broad range of topics and disciplines extending from tribology and corrosion to catalysis and deposition of thin films. This conference, held in Tokyo, Japan, focused on coatings. In particular, various thermal spray and vapor deposition processes were described and compared as a means of applying coatings and thin films, and the properties of such coatings were investigated and discussed.

## INTRODUCTION

The science of surface engineering has been important for decades to those concerned with tribology, corrosion, and catalysis. With the advent of chips for electronic devices, elegant fabrication procedures to deposit thin films of a variety of materials, sophisticated techniques to analyze and characterize surfaces, as well as the increasing interest in composites, the processes occurring on surfaces and at interfaces are of great importance. Consequently, over the past 10 to 15 years surface engineering has encompassed a much broader area of science.

An International Conference on Surface Engineering was held in Tokyo, Japan, from 18-22 October 1988. This was the first international conference to be held in Japan on surface engineering. It covered a wide range of technology, but thermal

spraying, painting, and vapor phase processing were emphasized. The conference was organized by the Japan Spraying Society, and Dr. Hideo Nagasaka, Emeritus Professor of Ibaraki University, served as general chairman. About 260 participants attended this 3-day conference, which was conducted predominantly in Japanese with discussions in both Japanese and English. Forty-seven papers were presented. The highlights of most of these papers are discussed in the following, and an assessment of the level of science and technology in Japan on these topical areas will be presented.

## THERMAL SPRAYING

In an invited paper, Kamachi, from Kinki University, reviewed the status of thermal spraying in Japan (P1)\*. It was stated that the thermal spray process is used for an ever-increasing spectrum of applications with corrosion-protective and wear-resistant coatings being two major applications. He used papers presented at the 1987 Annual Thermal Spray Society Meeting to highlight recent achievements and to indicate directions of future research.

Low-pressure plasma spraying (LPPS) was proposed as a technique of considerable potential for depositing ceramic materials such as borides, silicides, carbides, nitrides, and oxides. However, this method is not necessarily favorable for

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\*Paper titles are presented in the Appendix.

the preparation of nonoxide ceramics, and much work is needed to understand sublimation and decomposition of the feed powders in order to achieve coating homogeneity. At the present time, the more important research studies in Japan are concerned with the metallurgical and mechanical behaviors of coated structures. Accordingly, considerable interest is focused on structural characterization, surface preparation, surface modification, densification, and bonding in order to improve the properties of such coatings.

The plasma spraying of carbide coatings involves the complex interactions of thermal decomposition, oxidation, and phase transformations, the extent of which is governed largely by the processing gas environment. S. Oki of Kinki University reported on the transformations observed in the LPPS of WC-Co and SiC-Ni coatings in an Ar atmosphere at 30 mm Hg (P9). In particular his group noted that, unlike in open atmosphere spraying, the ternary phase of  $\text{Co}_3\text{W}_3\text{C}$  did not appear; they concluded that oxidation was inconsequential in the low-pressure process. Transformation from WC to  $\text{W}_2\text{C}$  and  $\text{Co}_3\text{W}_3\text{C}$  occurs in open atmosphere spraying through the thermal decomposition of the monocarbide and the loss of carbon by oxidation. In the deposition of SiC-Ni, oxidation reactions were also prevented. However, the sublimable loss of SiC was considerable although much of the Si was converted to  $\text{Ni}_2\text{Si}$ .  $\text{Ni}_2\text{Si}$  is a high-temperature phase. The fact that  $\text{Ni}_2\text{Si}$  forms during LPPS and not with open atmosphere spraying is indicative of a

higher thermal efficiency attributable to the increased residence time of the feed powders in the extended plasma jet of the low-pressure process.

### Coating Structure

Some papers were concerned with microstructures of plasma-sprayed coatings and correlations of structure to properties. Matsubara et al. (P7) investigated the microstructures of thermal-sprayed Co-21Cr-4.5W-3B\* coatings on low alloy steels with different carbon contents and subjected to various heat treatments. The heat treatment conditions necessary to minimize voids in the coatings were determined and the influence of carbon on such annealing conditions was described.

Knotek et al. (P8) described the properties of NbC-based films deposited on a titanium-stabilized austenitic steel and on a Nimonic 80 substrate by using the thermal spray process. Coatings prepared by using niobium carbide powder coated with cobalt and nickel were compared to coatings made using NbC powders and elemental nickel and cobalt powders. Properties of these coated systems, such as adhesion, wear, and thermal shock resistance, were better in the coatings prepared by using coated NbC particles; however, cracking was observed in thermal shock tests with coatings prepared by using nickel-coated NbC due to differences between the thermal expansion coefficients of the film and substrate. Coatings prepared by using coated powders were found to have no conversion of the

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\* All compositions are presented in weight percent unless indicated otherwise; for example, Co-21Cr-4.5W-3B indicates an alloy containing 21% Cr, 4.5% W, 3% B, and 71.5% Co.

NbC phase, whereas oxidation and carburization were evident for coatings made by using elemental powders of nickel and cobalt.

Bunya et al. (P2) developed an approach to measure the gas permeability of plasma-sprayed  $\text{Al}_2\text{O}_3$  and  $\text{Y}_2\text{O}_3$ -stabilized  $\text{ZrO}_2$  coatings. Gas permeability was found to decrease as the power of the plasma spray was increased. More dense coatings were obtained when an AEROPLASMA spraying system was used compared to a conventional plasma spray apparatus. This type of plasma torch is different from that of conventional spraying systems in that it can use air as a plasma gas, and powder for spraying can be fed directly into the arc.

Oki et al. (P26) investigated the structures of aluminide coatings on copper, carbon-steel, and austenitic stainless steel substrates. The aluminum was deposited by the wire arc spray method. The coatings were then heat treated for 4 to 11 hours at temperatures between 773 and 1,223 K. The phases that were formed in the coatings were identified by using x-ray diffraction, hardness measurements, and optical metallography.

### Modified Thermal Spray Techniques

Other techniques for depositing coatings involving spray processes were also described. Fukuda et al. (P10) used a wire explosion process to deposit TiC coatings on austenitic stainless steel. A capacitor discharge was used to melt TiC wires (1 mm diameter, 50 mm long) and form liquid particles of TiC that were sprayed onto the substrate to be coated. This process produced good coatings at pressures of 200 and

760 Torr. TiC coatings about 20 to 25  $\mu\text{m}$  thick were developed after six to seven wire explosion operations. The porosity of such coatings was about 4 vol %. Thermal shock resistance of the coated system was better than the substrate material and a piece of monolithic TiC. Ito et al. (P11) discussed WC-Co coatings that were produced by a wire explosion process and subsequently infiltrated with a low-melting copper alloy. WC-6.5Co coatings about 50  $\mu\text{m}$  thick were formed on mild steel after about 10 wire explosion exposures. These coatings were infiltrated with a Cu-9.6Ni-7.6P-4.2Sn alloy by placing a foil of this alloy upon the as-sprayed coatings and heating at temperatures between 973 and 1,113 K for 3 to 4 minutes in hydrogen. Most of the pores in the WC-Co coatings were filled with the alloy and the wear resistance of the infiltrated coatings was superior to that of the original coatings.

Low-pressure laser spraying (LPLS) using a wire feed has been used successfully in the past several years to produce Ti and other reactive material coatings. H. Shimura of the Mechanical Engineering Laboratory (MEL) reported similar accomplishments using LPLS with powder feed (P12). Coatings of Ti, Ni, Mo, and Cu-Sn were sprayed in an Ar or  $\text{N}_2$  atmosphere of 3 to 20 Torr. The LPLS technique is extremely useful for the deposition of reactive materials and, unlike the LPPS process, is not limited by a critical pressure below which spraying becomes unstable. However, for the LPLS technique, the use of powder feed does not appear to be more advantageous than the wire feed. On the contrary, the deposited materials typically show gas contamination exceeding that in the feed materials, i.e., ~725 ppm of  $\text{O}_2$  in Ti

wire and 1,500 to 3,500 ppm in powders. With respect to the cost, Shimura told the audience that MEL's CO<sub>2</sub> LPLS system was about \$1 million.

Takemoto and Enami (P13) described the effects of laser glazing thermospray and plasma-sprayed titania coatings on 304 stainless steel. Thermospray and plasma-sprayed titania coatings were deposited on 304 stainless steel plate by using the METCO 5P and 3MB spray guns, respectively. Coating thicknesses were varied between 300 and 500  $\mu\text{m}$  and various laser power densities and dwell times were investigated. The best conditions were obtained by using low laser powers and long dwell times; however, in no case could all defects be removed from the plasma-sprayed coatings. Some improvements were obtained by depositing organic or inorganic sealants in the plasma-sprayed coatings prior to laser glazing. The sealants were evidently absorbed in the plasma-sprayed coatings and caused new phases to be formed in the glazed layer.

In the preparation of substrates for spraying, N. Tani of Nagasaki Institute of Applied Science presented an extensive study on the effects of grit blasting and residual stress on ferritic and austenitic stainless steels (P14). This work was motivated by considerations about the importance of compressive residual stress to stress corrosion cracking and represents the initial phase of a study to improve thermal spraying procedures. Tani reported that both compressive residual stress and hardness varied in a similar manner with depth from the blasted surface and inferred that residual stress depends in a significant way on hardness and strain hardening coefficient of the specific material. In particular,

ferritic stainless steels, having higher hardnesses and strain hardening coefficients than austenitic stainless steels, sustain higher magnitudes of compressive stress at more shallow depths. These considerations are useful to determine the extent to which surface layers of grit-blasted materials must be removed prior to coating in order to realize the full benefits of residual stress.

### Properties of Thermal-Sprayed Coatings

M. Mayuram and R. Krishnamurthy of the Indian Institute of Technology submitted a paper (not presented) on a modified axial shear test for bond strength evaluation of thermal-sprayed coatings (P4). The study was motivated by concerns for deficiencies in existing test methods particularly with defining the nature and direction of the forces acting on the coating. The experimental procedure as described in the written paper consists of gripping a coated cylindrical rod with a collet assembly and displacing the rod axially until failure is produced in the coating. The authors reported that all the samples tested showed grip pullout and suggested that coating failure may occur with the use of a higher gripping force. It is not entirely clear that the modified axial shear test is viable and a computational analysis is needed to show otherwise.

Tobe et al. (P5) compared the rolling fatigue behavior of plasma-sprayed ceramic and metallic coatings on a carbon steel. The results were affected by the geometry of the test specimens. In the case of geometries where the coatings had overhanging edges, cracks were initiated at such sites, and the rolling fatigue strengths of both Al<sub>2</sub>O<sub>3</sub> and Cr<sub>2</sub>O<sub>3</sub> coatings were greater

than those for cobalt and molybdenum coatings. In the case of specimen geometries for which such overhanging edges did not form, the rolling fatigue strengths exhibited less scatter and the values for the metallic coatings were greater, becoming comparable to those for the ceramic coatings.

Kitamura et al. (P3) presented results on the corrosion resistance of wire flame-sprayed coatings of Zn, Al, or Zn-30Al on mild steel substrates when exposed to weathering tests in frigid zones. These tests were performed by exposing specimens at Hokkaido and at Tokyo over a period of 12 years. No remarkable differences were observed between the Hokkaido and Tokyo tests. All of the coatings provided protection to the substrate without substantial differences in performance of any of the coatings.

Steine et al. (P45) emphasized the importance of tailoring the composition of coatings to meet the specific requirements of the application. To use this approach the conditions of the application must be known and the effect such conditions have upon the coatings must be understood. Mechanisms of degradation were discussed but the level of his discussion indicated practical experience was being used in coating selection much more than in-depth understanding of the degradation processes.

Katoh et al. (P44) described nickel-chromium thermal-sprayed coatings that were developed to provide protection for AISI 304 used in a chemical synthesis reactor and for AISI 310 used in a high-temperature (800 to 1,200 °C) combustion gas. Their approach was totally empirical with testing consisting of simulated environments. The chemical synthesis environment involved a 15 wt. % KCl slurry solution

with pH = 4.5 at 200 °C. Increasing the chromium concentration resulted in increased coating lives. The combustion gas contained CO<sub>2</sub>, H<sub>2</sub>O, and O<sub>2</sub>. A Ni-50Cr coating was found to provide excellent resistance to the latter environment. No comments were presented in regard to the reasons that such a coating was effective. This coating provides protection by forming a Cr<sub>2</sub>O<sub>3</sub> scale, which usually is not very effective at temperatures above 1,000 °C.

Uchikawa et al. (P6) investigated the properties of plasma-sprayed CaO-SiO<sub>2</sub> coatings and compared results to those for yttria-stabilized zirconia. The performance of these coatings was dependent upon the CaO-SiO<sub>2</sub> molar ratio. The 2CaO-SiO<sub>2</sub> composition was reported to have low thermal conductivity and better thermal shock resistance than stabilized zirconia. It was also observed that this coating was more resistant than zirconia to an ash mixture containing 85V<sub>2</sub>O<sub>5</sub>-15Na<sub>2</sub>SO<sub>4</sub> at 900 °C. This mixture is not stable at 900 °C and will be converted to sodium vanadates having high activities of V<sub>2</sub>O<sub>5</sub>. The resistance of such a coating to Na<sub>2</sub>SO<sub>4</sub> deposits at 900 °C in air should be examined since the SiO<sub>2</sub> component may be attacked by such deposits when the Na<sub>2</sub>O activity is high.

Magome et al. (P25) studied the behavior of various plasma-sprayed coatings exposed to conditions encountered when used for dental implants. A pure aluminum coating about 100 to 150 μm thick and having a porosity of 15 to 30 vol % was found to give the best results. It was proposed that the porosity permits the bone tissue to grow into the coating. This coating became covered with an oxide when exposed to conditions of the human mouth; however, it was claimed that this oxide was compatible with tissue formation to achieve firm support.



The failure characteristics of thermal barrier coatings on a structural steel under the influence of thermally induced stresses were described by Mutoh et al. (P47). Coatings of  $8\text{Y}_2\text{O}_3\text{-ZrO}_2$ ,  $7\text{CaO-ZrO}_2$ , and  $22\text{MgO-ZrO}_2$  were prepared by using the plasma spray process. A bond coat of Ni-5Al was deposited via a flame spray process and thicknesses were varied from 0.1 to 0.3 mm. The coated specimens were subjected to a thermal cyclic test in which the temperature was varied between room temperature and 973 or 1,073 K. Coating lives increased as the bond coat thickness was increased since the bond coat prevented oxidation of the substrate. No significant effect of the stabilizers was observed.

Nagasaka et al. (P48) attempted to use thermally stimulated currents (TSC) and stimulated exoelectron emission (TSEE) to study structural imperfections in plasma-sprayed, calcia-stabilized zirconia. Since current flows in the coatings decreased with time after coating deposition, it was concluded that trapped carriers were present in the as-deposited coatings. An attempt was made to use the TSEE measurements to determine if the trapped carriers were electrons or ions. It was concluded that the trapped carriers were probably electrons.

Noji et al. (P46) investigated thermal-sprayed glass (e.g.,  $\text{SiO}_2\text{-B}_2\text{O}_3\text{-Na}_2\text{O-K}_2\text{O-Al}_2\text{O}_3\text{-NiO-MnO}$ ) on mild steel, where it was attempted to match thermal expansion coefficients by changing the composition of the glass. It was shown that dense thermal-sprayed coatings of glass could be obtained with no porosity. In order to have good adhesion it was necessary to preheat the substrate. The composition of

the glass coating was controlled to have its thermal expansion coefficient slightly less than the substrate, which produced small residual compressive stresses in the coatings. Different colors of these coatings were obtained by changing the concentrations of components such as  $\text{Fe}_2\text{O}_3$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{Cr}_2\text{O}_3$ ,  $\text{CaO}$ , etc. The mechanisms by which the color changes occurred were not described but must involve reactions with components in the glasses.

Sankawa et al. (P27) prepared thick films ( $\sim 70\text{ }\mu\text{m}$ ) of Y-Ba-Cu-O and Bi-Sr-Ca-Cu-O by plasma powder spraying. Feedstock powders were prepared by two methods, solid state reaction and coprecipitation. The powders were sprayed on a nickel alloy substrate using an atmospheric plasma powder spray apparatus (METCO 7MB system). The films were postannealed at 600 to 900 °C in flowing oxygen followed by furnace cooling. Superconducting films of Y-Ba-Cu-O were obtained with zero resistance observed at 88 K. In the case of Bi-Sr-Ca-Cu-O a low  $T_c$  phase was obtained with zero resistance observed at 50 K. Minehara et al. (P28) deposited films of superconductors by using a plasma spray painting technique. Particles of the powder materials were fed into an arc discharge and were sprayed onto the substrate. In order to achieve the correct stoichiometry and to provide adherence to the substrate, the particle size of the powder ranged from 20 to 100  $\mu\text{m}$  and the film was annealed at 550 to 650 °C for 12 hours. Superconductivity was observed for films of Y-Ba-Cu-O and Bi-Sr-Ca-Cu-O with results similar to those obtained with sintered specimens of these materials.

## VAPOR PHASE COATING PROCESSES

In an invited paper, K. Akashi of the Science University of Tokyo reviewed recent developments in plasma and ion processes (P34). He cited the Eighth International Symposium on Plasma Chemistry in Tokyo in 1987, the First Japan Symposium on Plasma Chemistry in Tokyo in 1988, and the continued support of the Ministry of Education for basic research programs such as the control of reactive plasma under Professor Itakuni of Kyoto University to illustrate the intense activity in this field. Currently, researchers are looking to ion implantation techniques that were developed for adding dopants to Si in the electronics industry to modify metallic, ceramic, and polymeric materials. For the surface modification of metals, ion implantation systems with high current and high accelerating voltage are necessary. Typically, plasmas from a microwave or a bucket source confined within a magnetic field have been developed for this purpose. The simultaneous application of vapor deposition with ion implantation, better known as ion beam enhanced deposition (IBED), is of particular interest in the formation of nonequilibrium phases. Cubic boron nitride and molybdenum nitride have been prepared by IBED using nitrogen ion implantation with an accelerating voltage between 25 and 40 keV and vapor deposition of boron or molybdenum. Plasma chemical vapor deposition (PCVD) using a glow discharge is an established low-pressure, low-temperature process. Recently, plasmas produced by electron cyclotron resonance have been studied with

respect to the higher degree of ionization and the prospect for achieving lower temperature reactions. Thermal plasma CVD is differentiated from PCVD in that the latter is sustained by an arc discharge and therefore the thermal process is not restricted to a reduced pressure. The most attractive application for thermal plasma CVD, besides its current use in the production of nanosize ceramic powders, is in the high rate deposition of ceramic coatings. This technique has been used successfully in the high rate deposition of diamond and high  $T_c$  YBCO films.

Chen et al. (P35) investigated the formation of diamond on silicon using microwave plasma CVD with gas mixtures of  $\text{CH}_4$  and  $\text{H}_2$  to which oxygen and  $\text{CO}_2$  were added. The silicon substrates were heated to 1,143 K. Substrate surface condition was found to affect deposition. Diamond films were formed on scratched substrates whereas diamond particles developed on the unscratched surfaces. The growth rates of both films and particles increased with the  $\text{CH}_4$  content and reached a maximum when the  $\text{CH}_4$  was 5 percent of the  $\text{H}_2$  volume. The maximum film and particle growth rates were 1.1 and 3.3  $\mu\text{m/h}$ , respectively. It was found that the addition of either  $\text{O}_2$  or  $\text{CO}_2$  to the  $\text{CH}_4$ - $\text{H}_2$  gas mixture increased deposition rates, and the intensities of diffraction peaks corresponding to those for crystalline diamond were increased. This latter result was used to conclude that these additives produce more crystalline diamond.

Murakawa et al. (P36) discussed the formation of diamond films on a WC-Co alloy substrate via CVD using ethanol as the raw material. The surface of the substrate

was polished with diamond paste. The ethanol was added to the system by bubbling hydrogen through liquid ethanol. The reaction pressure was 13 kPa with the ethanol 4 percent of the hydrogen volume. The substrate was heated to 700 to 900 °C. Diamond film deposition rates of 10  $\mu\text{m/h}$  were obtained and Raman spectra indicated that diamond had been formed along with some amorphous carbon. While not examined in these studies, the structures of such diamond films usually consist of columnar grains of diamond extending through the film with the amorphous carbon and/or graphite located at grain boundaries between the columnar grains. In this investigation the adhesive strength of the diamond coatings to the substrate was also evaluated. Presently, there are no quantitative tests suitable for measuring the adhesion of thick, hard coatings. Using a procedure similar to the operations of a metalworking shaper machine, Murakawa et al. measured the force required to shave off the coating and defined the adhesive strength as this force divided by the width of the shaved section. By studying relatively thin coatings, they were also able to determine adhesion using the diamond indentation method and reported an excellent correlation of adhesion data between the two test procedures. In a private communication, it was asked whether adhesion has been characterized as a function of coating thickness, particularly since this parameter has a dominating influence on the process of plastic deformation and fracture. For example, chips or turnings from shallow cuts can show curling and elongation even with glasses and ceramics. Murakawa said that this is the initial presentation on the

development of the shaper test and that the influence of coating thickness as well as cutting speed on adhesion is being investigated. In view of the fact that periodic cases of "slip-stick" cutting operations are observed, he indicated much work remains to be done to understand whether the coating removal process is associated more with deformation or with fracturing.

Arai et al. (P37) studied the deposition of TiC and TiN on steel by using plasma-assisted CVD. Prior to deposition the chamber was evacuated and  $\text{H}_2$  was admitted to the system and a dc glow discharge was ignited. Bombardment of hydrogen ions heated the substrate to temperatures between 400 and 700 °C. While still maintaining a stable dc glow discharge, reactive gases of  $\text{CH}_4$  (for TiC),  $\text{N}_2$  (for TiN),  $\text{TiCl}_4$ , and Ar were introduced up to a total pressure of 4 Torr. Deposition times were from 1.5 to 4 hours. Uniform coatings of TiN and TiC were obtained at rates of 1 to 3  $\mu\text{m/h}$ , depending on the reactive gas composition. The chlorine content in the TiN coatings increased drastically with decreasing deposition temperature below 550°C, while in the TiC coatings it increased below 475 °C. The hardnesses of the coatings continuously decreased with decreasing deposition temperature. The hardnesses of the coatings with a chlorine content of less than 5 wt. % were 3,000 and 2,000 HV for TiC and TiN, respectively, and continuously decreased with increasing chlorine content. The TiN and TiC coatings fabricated by this process exhibited high adhesive strengths compared to TiN coatings formed by ion plating and possessed outstanding wear and seizure resistance.

Tachikawa et al. (P38) reported on ion nitriding of aluminum alloys. A preliminary treatment of argon sputtering was used prior to ion nitriding using a nitrogen plasma. The preliminary treatment produced a highly irregular surface that was conducive to the formation of the nitride layer. This procedure was used on a variety of aluminum alloys and acceptable coatings were formed. The hardnesses of these coatings varied between 1,000 and 1,600 HV depending on the substrate alloy composition. Urao and Kosugiyama (P39) investigated the nitriding of titanium by using a subsidiary cathode to produce a stable glow discharge at specimen temperatures between 1,073 and 1,273 K. Nitrogen gas was introduced into the chamber at 4 Torr. After nitriding 1 to 4 hours, hard surface layers were formed containing TiN,  $Ti_2N$ , and  $TiO_2$ . Only TiN was formed upon nitriding 5 hours at 1,273 K.

Hasuyama et al. (P40) investigated ion beam induced mixing of titanium-coated alumina. Thin films of titanium (200 to 400  $\mu m$ ) were deposited on alumina substrates by rf sputtering. Ion bombardment was performed by using a 400-keV ion implanter whereby  $N_2$  ion energies were obtained sufficient to penetrate the titanium film at specimen temperatures of 300 to 500 K. The amount of mixing at the interface was characterized by using secondary ion mass spectroscopy (SIMS) and Rutherford backscattering (RBS). A large amount of mixing occurred at the Ti- $Al_2O_3$  interface at a specimen temperature of 500 K. This was attributed to the synergistic effect of the ion beam and specimen temperature. Krishnamurthy (P41) used ion implantation to affect the surface characteristics of high-strength, low-alloy (HSLA) steels. The surfaces were

implanted with  $N^+$  and  $B^+$  ions. Contact fatigue resistance was improved by using ion implantation. In spite of the fact that the  $N^+$  implantation did not enhance the surface hardness as much as  $B^+$ , the  $N^+$ -implanted surfaces yielded better results.

## POWDER AND PAINT COATINGS

In an invited paper, Erwin Bodnar of the DSM Powder Paint Company of France discussed the development trends of decorative and functional powder coatings in Europe (P15). Thermosetting powders are applied by spraying 100-percent dry paints consisting of resin-encapsulated pigment particles and curing the resin by heating. Thus, while the main components of powder coating and wet paints are similar, the powder coating process is quite different: it is solventless, is transported to the substrate by air, adheres by electrostatic attraction, and forms film by melting and outflowing. Bodnar reported that the 1987 thermosetting powder market in western Europe was 90,000 tons and is projected to double within the next 10 years. About 50 percent of the demand will consist of building structures, household appliances, metal fixtures, and machinery. One of the fastest growing segments of this industry is in the use of powder coatings for architectural aluminum. This outlook has led major aluminum anodizing companies in Europe to invest in powder coating facilities.

Satoh and Kogure of Kansai Paint Company reported on the physico-chemical properties of paint film and corrosion protection of painted steels (P19). Using an acid/base concept to characterize paints, his group calculated the contribution to surface tension by hydrogen bonding,  $\gamma^h$ , for

different polymeric resins and obtained a direct correlation with the corrosion resistance of the resin-coated steel samples. Since  $\gamma^a$  is a measure of the work of adhesion, the increase in corrosion resistance is viewed as a manifestation of adhesion between the polymer coating and the oxide surface of the metal. Hydrogen bonding is one aspect of the generalized acid/base concept used in the characterization of pigments and binders in paints. In the same manner that pH can be used to express acid/base strengths in a water system, hydrogen bonding can be expressive of the donor-acceptor strength of solvents and pigments.

Yasui (P18) described a new flame spraying process capable of coating unpreheated metal with a plastic material highly resistant to chemicals and corrosion. A nonporous and highly adhesive coating was formed by flame spraying of a powderlike material consisting of polyethylene against metallic surfaces precoated with an adhesive primer. Coating thicknesses from  $\sim 500 \mu\text{m}$  to a few millimeters could be formed.

Okuda (P20) described an experimental method for comparing the effectiveness of organic coatings in various aqueous media by using weight change versus time measurements of coated specimens. The useful life of the coating was taken as the time required for the corrosive liquid to be fully absorbed into the coating followed by a saturation stage during which no weight change occurred. The onset of weight changes after the saturation stage was caused by corrosion of the metallic substrate and indicated failure of the coating.

Tsubota and Shinden (P21) studied the relationship between the abrasion resistance and the mechanical properties of

various organic coatings. They concluded that the abrasion resistance was not related to hardness, tensile strength, or breaking energy of the coatings (area under the stress-strain curve). For films with pigments the abrasion resistance did increase with the elastic breaking energy. A mechanism was developed to account for such results by examining the abrasion process.

Kawashima et al. (P22) investigated the properties of coating films used as lapping tapes for precision finishing and polishing of electronic materials, magnetic heads, floppy disks, hard disks, etc. Parameters of the tape such as grain shape, grain size, grain content, binder resin, and base film type were considered in regards to their effect on properties. The grain shape in the lapping film had a marked effect on the lapping properties. Stock removal decreased in the following order as a function of grain shape: spherical > polyhedral > blocky > platelike. Smaller surface roughnesses of lapped surfaces were obtained for the following order of grains: platelike > blocky > polyhedral > spherical. Although the film of spherical grains had the highest stock removal rate, the resulting surface was scratched and rough. Polyhedral-shaped grains gave high stock removal rates with a relatively fine finish to the lapped surface.

N. Miyazaki of Asahi Glass Research Center (P23) reported on the developments of a new fluoropolymer for coating applications. Fluoropolymers are highly heat and chemical resistant and, for the paint industry, processibility needs to be improved before fluoropolymers can be used with greater efficiency. In the present work, processibility was improved through the copolymerization of fluoroethylene and

alkyl vinyl ether (FEVE). The incorporation of alkyl vinyl ethers provided the polymers with greater solubility and cross linking reactivity, while the control of OH and COOH groups in the ethers largely regulates the curing conditions and compatibility with pigments. The data on accelerated and natural weathering tests showed FEVE to be superior to polyvinylidene fluoride and acrylic urethane in corrosion protection and color and glass retention. These differences were brought out dramatically on slide projections showing comparisons of automobile paint finish.

### MISCELLANEOUS COATING PROCESSES

Using a different approach to ceramic composites, S. Ohtani et al. reported on the use of second-phase metallic powders to improve the thermal shock resistance of ceramic coatings (P24). In this process,  $\text{Cr}_2\text{O}_3$  matrix composite coatings are formed by dipping samples in a chromic acid slurry containing dispersed particles of  $\text{SiO}_2$  and stainless steel, converting the chromic acid film to  $\text{Cr}_2\text{O}_3$  at 550 °C, and densifying by repeated infiltrations with chromic acid and intermediate calcining. Water quench data were presented showing  $\text{Cr}_2\text{O}_3$ -50 vol %  $\text{SiO}_2$  coated stainless steel (SS) samples (CDC-S) to have a thermal shock value of 700 °C while  $\text{Cr}_2\text{O}_3$ -25 vol %  $\text{SiO}_2$ -25 vol % SS particles (SUS-50) increased to 900 °C. Acoustic emission measurements during heating and quenching in Ar also showed a remarkable reduction in echoes generated in SUS-50. The authors attributed the improvements to the increased ductility in SUS-50 and a thermal expansion characteristic more closely

resembling that of the substrate. The thermal expansion behaviors of CDC-S and to a lesser extent SUS-50 show plateaus at about 700 °C. In a private communication, Ohtani said the plateau regions originate from the transformation of  $\alpha$ - $\text{SiO}_2$  to the  $\beta$ -form. Thus transformation stresses are responsible for the observed surface cracks and the associated acoustic emission activity on heating to 700 °C. The acoustic emission activity occurring on cooling below 150 °C is due to detachment of the coating by flaking. Additional improvements in thermal shock were obtained by incorporating only SS particles in the  $\text{Cr}_2\text{O}_3$  coating. Obviously, the nature of the disperse phase will have an influence on the composite hardness. Typical hardness values are 1,500 HV for CDC-S, 1,050 HV for SUS-50, and 800 HV for  $\text{Cr}_2\text{O}_3$ -50 vol % SS particles.

Tosa and Yoshihara (P42) examined the adherence of ceramic coatings on 304 and 321 stainless steels. Coatings of  $\text{Si}_3\text{N}_4$  and  $\text{Al}_2\text{O}_3$  were deposited by using rf magnetron sputtering while TiC coatings were formed by using ion plating. Coating thicknesses ranged from ~10 nm to about 1  $\mu\text{m}$ . The coated specimens were annealed at 1,100 K in vacuum for 1 hour. All of the coatings cracked and spalled from 304 but were adherent to 321. They concluded that the annealing of the coatings on 321 improved the adherence due to diffusion of titanium and carbon to the coating-alloy interface, which resulted in TiC formation. Similar conditions evidently did not develop in the case of 304, but sulfur was detected at the coating-alloy interface, which was proposed to cause spalling of the coatings during cooling. The authors did not present details on why these processes may occur in the case of one substrate and

not the other. The titanium concentration in 304 was reported to be 0.003 compared to 0.420 in 321, while the sulfur levels were 0.008 and 0.006, respectively. It would be of value to determine if the titanium concentration is a critical parameter in order to have adherence of these ceramic coatings to stainless steel substrates.

Shinoda (P49) investigated the use of laser melting to prevent preferential, intergranular corrosion in weld heat-affected zones of AISI 304 that occurs due to chromium carbide formation with depletion of chromium from grain boundary regions. It was found that laser beam scanning can be used to remove sensitized weld heat-affected zones in AISI 304 by dissolving any precipitated carbides.

## CONCLUDING REMARKS

This conference emphasized those aspects of surface engineering most closely related to practical uses. Many papers dealt with techniques to apply coatings and their properties. Much less emphasis was placed on the chemistry and physics of surfaces and interfaces.

The level of the thermal spray technology in Japan is as advanced as that in the United States with some qualifications. The Japanese technology appears to be closely following the U.S. and European technologies. For example, there is currently much interest in Japan in the low-pressure plasma spray process and the use of ceramic coatings applied via LPPS, while LPPS has been widely used in the United States for both metallic and ceramic coatings for more than 10 years.

The vapor phase deposition technology in Japan is extensive and impressive.

Much developmental research is being performed at industrial, governmental, and university laboratories. The level of this technology in Japan is as advanced as any country in the world. Very much work is being performed on deposition of diamond coatings and a variety of ceramic coatings such as SiC, TiC, Si<sub>3</sub>N<sub>4</sub>, TiN, and Al<sub>2</sub>O<sub>3</sub>. A large number of processes to deposit coatings are being investigated, including CVD in conjunction with techniques to produce activated species such as thermal, laser, microwave, dc discharge, etc.; physical vapor deposition; molecular beam epitaxy; sputtering; and ion implantation.

The papers presented at this conference are not indicative of the level of technology in Japan on the use of paints and polymeric coatings since the conference did not include a significant number of polymer engineers. Polymer research in Japan is very extensive and advanced. The level of paint and polymer coating technology is as advanced as any country in the world.

Finally, it should be mentioned that the Japanese interest in surfaces has been primarily directed to applications involving ambient temperatures to about 700 °C. It is evident that their technology for such low-temperature applications is highly advanced especially in regards to modification of surfaces to obtain certain desirable properties. For such cases new approaches with unique results are evident and can be expected to continue. Japanese interest in higher temperature applications has developed more recently and the current technology is following the U.S. technology. The Japanese technology for such cases is developing experience in techniques and processes that are state-of-the-art in the United States.

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## Appendix

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Kazuyoshi Kamachi  
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**P2 Gas Permeability of Plasma-Sprayed Coating**

A. Bunya, T. Itoh, H. Saitoh, and M. Shimoizumi  
Ionics Div.  
Onoda Cement Co., Ltd.

Y. Ohno and Y. Kaga  
Electrotechnical Laboratory

**P3 Corrosion Resistance of Metal Sprayed Coatings in a Frigid Zone**

Dr. Yoshiharu Kitamura and Mitsugu Shima  
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Hokkaido Institute of Technology

Kazuo Ishikawa and Masao Seki  
Tokyo Metallikon Co.

Dr. Hideo Nagasaka  
Professor Emeritus, Faculty of Engineering  
Ibaraki University

Dr. Sosuke Uchida  
Uchida Metal Research Office

Shinichi Yoshida  
Japan Steel Structure Painting Association

**P4 Modified Axial Shear Test for Bond Strength Evaluation of Thermal Sprayed Coatings**

M.M. Mayuram and R. Krishnamurthy  
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**P5 Rolling Fatigue Behaviour of Plasma Coated Steel**

**Shogo Tobe, Shotaro Kodama, and Kouhei Sekiguchi**  
Tokyo Met. Univ.

**Kazuo Ishikawa**  
Tokyo Metallikon Co., Ltd.

**P6 Properties of the CaO-SiO<sub>2</sub> System Plasma-Sprayed Coatings**

**Hiroshi Uchikawa, Hiroshi Hagiwara, Masaru Shirasaka, and Hiroshi Yamane**  
Onoda Cement Co., Ltd.  
Ceramics Research Laboratory

**P7 Microstructural Variation of Thermal Sprayed Co-Cr-W-B Alloy Coatings Due to Diffusion Treatment**

**Yasuhiro Matsubara and Kazumaru Kohira**  
Kurume College of Technology  
Department of Materials Science & Metallurgical Engineering

**Kazunori Sakata and Tetsuo Uchibayashi**  
Fujiki Kosan Corp.  
Engineering Department

**P8 Thermally-Sprayed NbC-Based Hard Material Coatings**

**O. Knotek, R. Elsing, and I. Pragnyono**  
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**Sachio Oki, Susumu Gohda, and Kazuyoshi Kamachi**  
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**P10 TiC Coating on Metallic Substrates by Wire Explosion Spraying**

**S. Fukuda, T. Matsubara, Y. Aono, T. Muroga, Y. Takao, and N. Yoshida**  
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**K. Tokunaga**  
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**P11 Infiltration of Copper Alloy into Wire Explosion Sprayed WC-Co Coatings**

**Hiroshi Ito and Ryoza Nakamura**  
Department of Materials Science & Metallurgical Engineering  
Kurume College of Technology

**Shuichi Imasato and Kei Tokumoto**  
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Nippon Tungsten Co., Ltd.

**P12 Wear-Resistant Metal Cladding by Low Pressure Laser Spraying**

**H. Shimura and Y. Enomoto**  
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**H. Ohtomo and T. Yamaguchi**  
Suzuki Motor Co., Ltd.

**P13 Laser Surface Glazing of Oxide Ceramics**

**Mikio Takemoto and Yoshihide Enami**  
Faculty of Science and Engineering  
Aoyama Gakuin University

**P14 Residual Stresses on Grit Blasted Surface of Steels**

**Noboru Tani, Tsuyoshi Ishida, and Masakazu Kawano**  
Nagasaki Institute of Applied Science

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**Erwin Bodnar**  
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**P16 The Paint Film Properties of Powder Coating for PCM (Pre-Coated Metal)**

**M. Uchida**  
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**S. Takata**  
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Products Laboratories  
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**N. Usui**  
Technical Planning Section  
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**Toshiyuki Yasui  
Technical Research Center  
NKK**

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**Tadaaki Satoh and Hideo Kogure  
Research Laboratory  
Kansai Paint Co., Ltd.**

**P20 Life Evaluation of Organic Coating Under Permeation of Environments**

**S. Okuda  
Doshisha University**

**P21 Abrasion Resistance of Coating Films**

**M. Tsubota  
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**N. Shinden  
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**P22 The Coating Film Properties of Lapping Tapes**

**Norimichi Kawashima, Kazuya Orii, Toshiro Hattori, Hiroshi Hosaka, and Shigezo Tochiara  
Tokyo Magnetic Printing Co. Ltd.**

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Asahi Glass Research Center**

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**Saburo Ohtani, Hiroshi Kubo, Tsugio Ishida, Takeshi Nishikawa, and Katsuhiro Kawashima  
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**M. Magome and S. Ogawa  
Osaka Sangyo University**

**K. Tsutsumi, V. Ohtori, and K. Imanishi  
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Sachio Oki, Kazuyoshi Kamachi, Susumu Gohda, and Toru Ito  
Faculty of Science and Engineering  
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Gunji Ueno  
Kanmeta Engineering Co., Ltd.

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Izumi Sankawa, Tsuneo Konaka, and Koshi Ishihara  
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E. Minehara  
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T. Sakamoto and O. Takano  
Himeji Institute of Technology

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H. Koyano and M. Ichikawa  
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Hironobu Nuriya and Yoshiharu Kitamura  
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**Xu Binshi**  
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Beijing Polytechnic University

**Ma Shining and Huang Yanbin**  
Surface Engineering Research Institute of Chinese Mechanical Engineering Society

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**K. Akashi**  
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**Chia-Fu Chen and Yen. C. Huang**  
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**Satoru Hosomi and Isao Yoshida**  
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**M. Murakawa, S. Takeuchi, and Y. Hirose**  
Nippon Institute of Technology

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**Tohru Arai, Hironori Fujita, and Kazuyuki Oguri**  
Toyota Central R&D Labs, Inc.

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**Hideo Tachikawa, Hironori Fujita, and Tohru Arai**  
Toyota Central R&D Labs, Inc.

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**Ryoichi Urao and Masao Kosugiyama**  
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N. Hayashi and I. Sakamoto  
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**P41 Performance Characteristics of Ion Implanted Sliding Surface**

R. Krishnamurthy  
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M. Tosa and K. Yoshihara  
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Hiroshi Ike and Akitake Makinouchi  
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Mikio Kimura  
Master Course Student  
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Takashi Katoh, Hiroshi Saito, and Moto Nakajima  
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H.T. Steine and C. Wasserman  
Castolin S.A.  
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Hideharu Noji, Nobuhiko Hara, Takahiro Tsutsumoto, and Hiroki Yokoyama  
Industrial Research Institute  
Hiroshima Prefecture West

Hiromi Kondo  
Liton Co., Ltd.

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Y. Mutoh, I. Sakamoto, and T. Nishimura  
Nagaoka University of Technology

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Hideo Nagasaka  
Emeritus Professor  
Ibaraki University

Yoshihiro Momose and Manabu Takeuchi  
Faculty of Engineering  
Ibaraki University

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T. Shinoda  
Nagoya University

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Xi Hongzhuo, Qu Peihua, Li Guangying, and Gemengzhou  
Hubei Institute of Technology  
People's Republic of China

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# SPACE COMMERCIALIZATION TECHNOLOGY INFORMATION GROUPS IN JAPAN

Frederick R. Best

**T**his article describes the socio-political conditions that led to the creation of organizations whose purpose is to smooth Japan's transition into the space industrialization age. The Space Technology Research and Development Group of Japan is presented as an example of such an organization.

## INTRODUCTION

During the post-World War II era, the Japanese have been very successful at importing technology, refining and adapting it to produce highly salable export items. More recently, Japan has come to recognize that its position as a technological leader depends on expanding the basic store of scientific information. The Science and Technology Agency, Japan's highest scientific deliberative body, published a White Paper dated 10 February 1988 in which it said that Japan "should promote its own unique science and technology while fulfilling its international duties as one of the world's advanced countries and maintaining its competitive and collaborative relationships with other countries."

Japan has identified the commercialization of space as a high payoff technological area. The Japanese Space Activities Commission estimates that the market scale of the Japanese space industry will be ¥1 trillion annually by the 21st century. This

article describes the socio-political conditions that led to the creation of organizations whose purpose is to smooth Japan's transition into the space industrialization age. The Space Technology Research and Development Group of Japan (SPAT) is presented as an example of such an organization. This article concludes with comments on the lack of SPAT-like organizations in the United States.

## BACKGROUND

The Japanese Government Space Activities Commission published a long-term planning document in May 1987 titled "Toward a New Era of Space Development." The report details Japanese space successes such as the "Sakigake" Halley's comet mission, the launching of the H-1 rocket (capable of lifting 550 kg to geostationary orbit), as well as communications and earth resources observation satellites. The report describes how delays in the U.S. shuttle program following the Challenger accident have not only delayed Japanese experiments designed to fly on the shuttle but also degraded Japan's space capability *vis-a-vis* the European, Chinese, and Russian programs. The Space Activities Commission concluded that Japan should have a policy for conducting independent space research in the future, including manned flights. In the same time frame, the Science and Technology Agency

announced that its previous policy of "no manned space activities" would be replaced by a program calling for "investing ¥6 trillion over a 15-year period and to commence manned space activities ... in the latter half of the 1990s." The Space Activities Commission concurred in this decision. This program is to be conducted in addition to the comprehensive promotion and development of the U.S. space station Japanese Experiment Module. Furthermore, the Science and Technology Agency directed that science and technology should be coordinated to include internationally capable researchers and organizations. Japanese organizations carrying out these activities are to be promoted by a financial system of preferential tax treatment and loan granting.

It is within this framework of societal and technological change, as well as financial assistance, that commercial organizations have been created to promote the utilization of space. The following section of this article presents an overview of five such organizations, together with more detailed information on the plans and activities of one of these companies.

## **SPACE COMMERCIALIZATION/ INFORMATION GROUPS**

Five major groups have been formed to promote information exchange and the commercial utilization of space and the space station. Four of these together with their major sponsors are listed below:

1. Marubeni Group -- Nissan Motor Corp. and Hitachi Ltd.
2. Mitsui and Company Group -- IHI and Toshiba
3. Sumitomo Group -- Nippon Electric Co.
4. Mitsubishi Group -- Mitsubishi Heavy Industry and Mitsubishi Electric

The fifth group, SPAT, has been active recently in the United States and it is this group that is detailed below.

SPAT was formed on 16 November 1984. The objective of SPAT is to determine by technical studies and reviews of research the route to commercial utilization of the space station. SPAT's activities include:

- Studying the prospects for space station commercial utilization.
- Collecting and analyzing information from within Japan and internationally. This is to include the transfer of technology.
- Conducting research on experiments for the space station, the space shuttle, and "get away" specials.
- Arranging lectures, meetings, and visits on space-related topics.
- Contacting and exchanging information with space-related organizations and governmental agencies.

- Conducting other activities that may be necessary to meet the above objectives.

SPAT is directed by a chairman and presently has three main functioning divisions: materials, life sciences, and research/information. Figure 1 shows SPAT's organization and the companies actively participating in each division. The

Nissho Iwai Corporation is the main motivating force for SPAT. Note that the chairman and chief advisors have held or are holding very prestigious positions, indicating that SPAT is highly visible within the Japanese space technical hierarchy.

SPAT presently has 50 member companies and promoters as listed below:

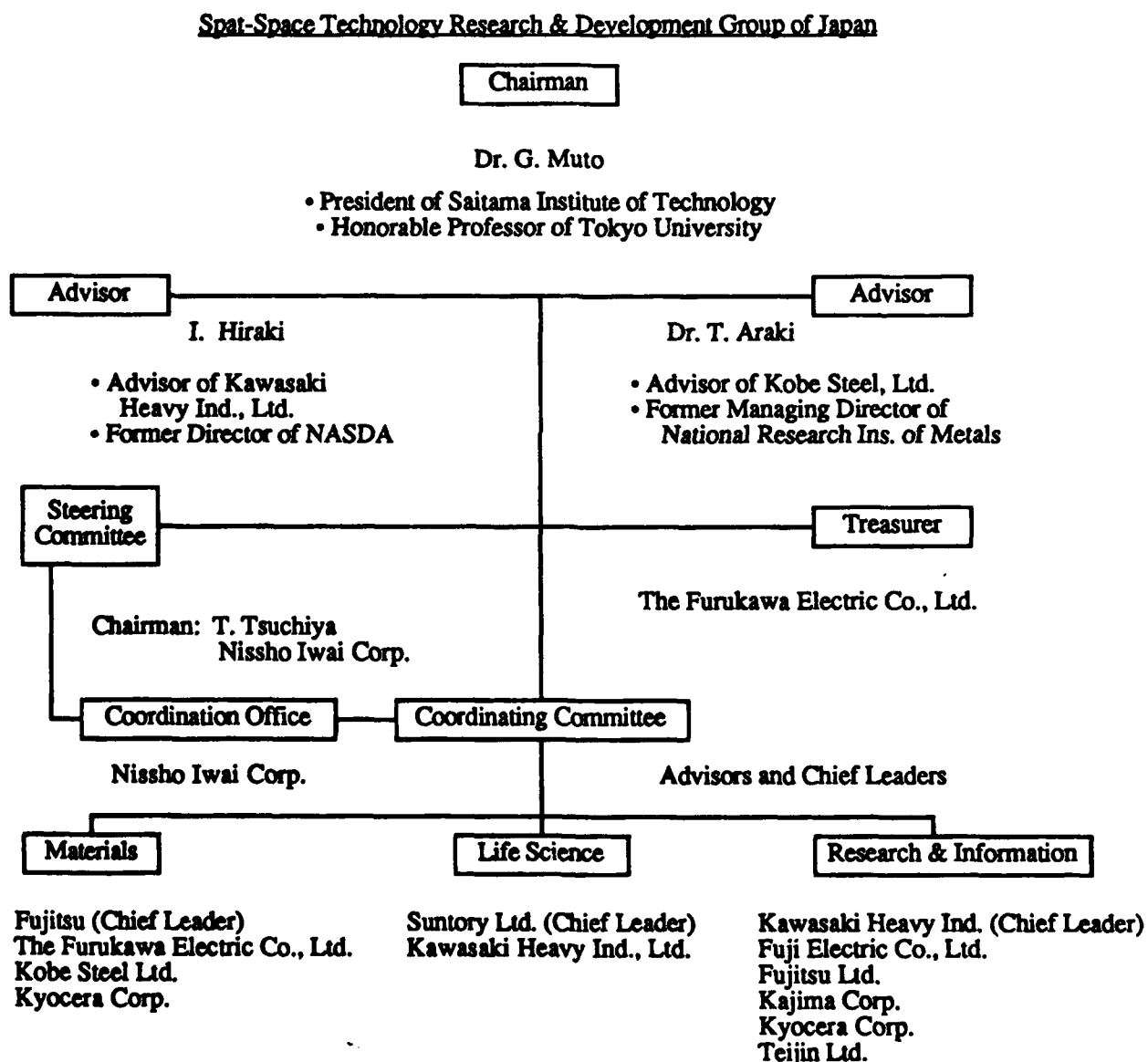


Figure 1. SPAT organization chart.

**Promoters:**

*Nissho Iwai Corp.\**  
*Kawasaki Heavy Industries, Ltd.*  
*Kobe Steel, Ltd.*  
*Kyocera Corp.*  
*Suntory Ltd.*  
*Teijin Ltd.*  
*The Furukawa Electric Co., Ltd.*

**Members:**

Central Glass Co., Ltd.  
Daicel Chemical Industries, Ltd.  
Ebara Corp.  
Fuji Electric Co., Ltd.  
Fujitsu Ltd.\*  
Hitachi Ltd.\*  
Hitachi Zosen Corp.  
Japan Airlines  
Japan Radio Co., Ltd.  
Japan Tobacco Inc.  
JGC Corp.\*  
Kajima Corp.\*  
Kansai Paint Co., Ltd.  
Kawasaki Kisen Kaisha, Ltd.  
Kawasaki Steel Corp.  
Kayaba Industry Co., Ltd.  
Koito Manufacturing Co., Ltd.  
Kokusai Kogyo Co., Ltd.  
Meisei Electric Co., Ltd.\*  
Mine Bea Co., Ltd.

NHK Spring Co., Ltd.  
Nippon Rokaki Co., Ltd.  
Nisshin Steel Co., Ltd.  
NTN Toyo Bearing Co., Ltd.  
Sankyo Co., Ltd.  
Sansui Electric Co., Ltd.  
Sasakura Engineering Co., Ltd.  
SECOM Co., Ltd.  
Shimadzu Corp.  
Shimizu Construction Co., Ltd.  
Shionogi & Co., Ltd.  
Sintokogio Ltd.  
Taiyo Fishery Co., Ltd.  
Tanabe Seiyaku Co., Ltd.  
Teijin Seiki Co., Ltd.  
The Furukawa Battery Co., Ltd.  
The Nohmibosai Kogyo Co., Ltd.  
The Yokohama Rubber Co., Ltd.  
Toa Wool Spinning & Weaving Co., Ltd.  
Tokuyama Soda Co., Ltd.  
Ube Industries, Ltd.

It is important to note that some of these companies might be thought to have little interest in space. There is some indication that they support SPAT as a matter of supporting Japanese national goals. In any case, SPAT presents lectures and seminars to all of these companies, supplying general

information about space and its commercial possibilities as well as specific information/studies for "promoter" members. This information comes not only from domestic Japanese sources but also from international sources including fact finding trips.

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\*Individuals from these organizations participated in the September-October 1988 fact finding trip to the United States.

The most recent fact finding trip took place during September-October 1988 when a five-member SPAT group visited over eight different National Aeronautic and Space Administration (NASA), university, and laboratory sites in the United States. The purpose of the visit was to observe and collect the latest information as well as make personal contact with the researchers. Examples of the sites visited include the NASA Johnson Space Center, Kennedy Space Center, Huntsville, Marshall, Jet Propulsion Laboratory, and the NASA Center for the Commercial Development of Space Power at Texas A&M University. The members of the SPAT group were generally high level personnel including general managers, chief engineers, and engineering division heads, and all were technically oriented. The size of the group, the high level technical capability of the participants, and the resources dedicated to the trip indicate that SPAT expects to obtain a significant return on its investment.

Interviews with several high level SPAT executives disclosed several near-term considerations. The September-October visit, as well as discussions within SPAT and with its promoters, will result in decisions to seek funding from various sources within Japan in addition to SPAT-participating organizations. In particular, SPAT may seek financial support from the Ministry of International Trade and Industry to investigate/encourage participation of industrial, not specifically aerospace, corporations. This could include chemical and pharmaceutical companies

but could also include distillers and entertainment organizations. SPAT may seek financial support from the Science Technology Agency/NASDA in the area of space technology. This would involve support directly in the area of aerospace-related companies, including civil engineering companies that may be involved in the planning and contribution of vast new spaceport facilities. The Ministry of Education might be approached for financial support directed via universities to support research in fundamental and applied space technologies. It is important to note that SPAT has potentially more organizations to appeal to for support than a comparable U.S. company.

The Science and Technology (S&T) Agreement\* signed in June is designed to provide a framework for increased technological interaction between the two countries. SPAT was familiar with the agreement but thought that it was going to affect mostly end-use technology and that since this was only a part of SPAT's work there would not be a big change in SPAT's activities. This would seem to be a very narrow reading of the S&T Agreement. Certainly the impact of the agreement has not yet begun to be felt by U.S. companies and it may therefore be some time before organizations such as SPAT are fully able to appreciate its impact. This would be an interesting area to reinvestigate with SPAT after a year or two.

SPAT also felt that Japan's recent decision to enter the manned space flight arena would have little impact on its planned activities. Nevertheless, it would

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\*"Cooperation in Research and Development in Science and Technology," Toronto, Canada, 20 June 1988.

seem that Japanese manned space flight could change the whole future of SPAT's commercialization plans. This apparent inconsistency may be just a matter of the different time frame of the commercialization activities (beginning in 1984) and manned activities (scheduled to begin in the late 1990s).

## SUMMARY

An infrastructure of companies dedicated to bringing space commercialization to Japan exists. These organizations have support from industrial giants and have the Government's attention as well. They are actively seeking overseas technology to smooth Japan's entry into the market. As of 1988 there have been no major financial results from their efforts, but the programs are intensifying and growing. The projected market has attracted the interest of many of the financial giants in Japan, and even companies that expect no

financial return seem to support the space commercialization efforts as a matter of national pride. Recent changes in Japanese manned flight policy and technology agreements with the United States have not yet impacted the plans of organizations such as SPAT. It would be useful to the United States to study how SPAT and SPAT-like organizations succeed in enhancing the Japanese space commercialization efforts in order to see how such approaches could be used in the United States.

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*Frederick R. Best received his Ph.D. in nuclear engineering from the Massachusetts Institute of Technology. Interphase transport phenomena are his areas of interest. He is presently an associate professor of nuclear engineering at Texas A&M University and a reserve CDR with the ONR/NRL 410 Unit in Houston, Texas. Experimental zero gravity heat transfer and fluid flow are his current major projects.*

# INTERNATIONAL MEETINGS IN THE FAR EAST 1989-1994

Compiled by Yuko Ushino

The Japan Convention Bureau, the Science Council of Japan, and journals of professional societies are the primary sources for this list. Readers are asked to notify us of any upcoming international meetings and exhibitions in the Far East which have not yet been included in this report.

1989			
Date	Title/Attendance*	Site	Contact for Information
March 12-16	International Symposium/ Information Transduction and Processing in Biological Systems - From Cell to Whole Body  8-F80-J190	Takamatsu, Japan	Department of Physiology Kagawa Medical School 1750 Ikenobe, Miki-cho Kita-gun, Kagawa-ken 761-07
March 13-16	The 1st JHPS International Symposium on Fluid Power Tokyo	Tokyo, Japan	FLUID-POWER TOKYO '89 Secretariat Attn: Mr. R. Miura The Japan Hydraulics & Pneumatics Society Kikaishinko Kaikan No. 301-3 3-5-8 Shiba-koen Minato-ku, Tokyo 105
March 15-17	International Workshop on Intelligent Materials	Tsukuba, Japan	Secretariat: International Workshop on Intelligent Materials The Society of Non-Traditional Technology Toranomon Kotohira-Kaikan Bldg, 3F 1-2-8 Toranomon Minato-ku, Tokyo 105 Attn: Mr. Tsunehisa Kurino
April 3-7	IFIP TC-2 Working Conference on Visual Database Systems  15-F30-J60	Tokyo, Japan	Professor Toshiyasu L. Kunii Department of Information Science Faculty of Science, University of Tokyo 7-3-1 Hongo Bunkyo-ku, Tokyo 113
April 10-12	International Workshop on Industrial Applications of Machine Intelligence and Vision (MIV-89)	Tokyo, Japan	Professor Mitsuru Ishizuka Institute of Industrial Science University of Tokyo 7-22-1 Roppongi Minato-ku, Tokyo 106
April 10-14	1989 National Engineering Conference	Perth, Australia	Conference Manager 1989 National Engineering Conference The Institution of Engineers, Australia 11 National Circuit Barton ACT 2600

\*Note: Data format was taken from the Japan International Congress Calendar published by the Japan Convention Bureau.

No. of participating countries  
F: No. of overseas participants  
J: No. of Japanese participants

1989

Date	Title/Attendance	Site	Contact for Information
April 10-14	International Symposium for Electro-Machining (ISEM-8)	Nagoya, Japan	Secretary of the Organizing Committee Professor Takahisa Masuzawa Institute of Industrial Science University of Tokyo 7-22-1 Roppongi Minato-ku, Tokyo 106
April 10-15	International Conference on Modernization of Steel Rolling	Beijing, People's Republic of China	ICMSR Secretariat Chinese Society of Metals 46 Dongsixi Dajie Beijing
April 11-14	International Symposium on Ship Resistance and Powering Performance (ISRP)	Shanghai, People's Republic of China	International Symposium on Ship Resistance and Powering Performance Department of Naval Architecture and Ocean Engineering Shanghai Jiao Tong University Shanghai
April 11-14	International Symposium for Electro-machining (ISEM 9)  16-F50-J300	Nagoya, Japan	Japan Society of Electrical-Machining Engineers c/o Institute of Industrial Science University of Tokyo 7-22-1 Roppongi Minato-ku, Tokyo 106
April 11-14	The 5th International Meeting of the Polymer Processing Society	Kyoto, Japan	Professor T. Matsuda Research Center for Medical Polymers and Biomaterials Kyoto University Shogoin, Sakyo-ku, Kyoto
April 12-14	The 22nd JAIF Annual Conference  25-F150-J1,100	Tokyo, Japan	Japan Atomic Industrial Forum, Inc. Toshin Bldg 1-1-13 Shimbashi Minato-ku, Tokyo 105
April 18-21	The 2nd Asian Fisheries Forum  30-F150-J150	Tokyo, Japan	Secretariat: The 2nd Asian Fisheries Forum c/o Faculty of Agriculture Tokyo University 1-1-1 Yayoi Bunkyo-ku, Tokyo 113
April 23-27	The 4th Wire Asia, Conference and Exhibition	Shanghai, People's Republic of China	Exhibitions for Industry Ltd. 110-112 Station Road East Oxted, Surrey RH3 0QA, UK
April 24-29	The 4th International Conference on Langmuir-Blodgett Films  NA-F150-J300	Tsukuba, Japan	Dr. Kiroo Nakahara Secretary General of 4th-LB Conference Saitama University Urawa 338
April 25-28	The 9th International Conference on Nondestructive Evaluation in the Nuclear Industry	Tokyo, Japan	Member/Customer Service ASM International OH 44073 U.S.A.
April 26-28	International Symposium on Pressure Vessel Technology and Nuclear Codes & Standards	Seoul, Korea	Dr. Byung-Koo Kim Korea Advanced Energy Research Institute P.O. Box 7 Daeduk-Danji, Chungnam, Korea 301-353



1989

Date	Title/Attendance	Site	Contact for Information
April 26-28	1989 Japan International Electronic Manufacturing Technology Symposium	Nara, Japan	1989 Japan IEMT Symposium c/o International Communications, Inc. Kasho Bldg., 2-14-9, Nihonbashi Chuo-ku, Tokyo 103
May 9-12	The 2nd IMEKO TC 14 International Symposium on Metrology for Quality Control in Production	Beijing, People's Republic of China	ISMQC/IMEKO 89 Mr. Zhang Zhihai National Organizing Committee c/o Chinese Society for Measurement P.O. Box 1413 Beijing
May 9-12	International Conference on Electrical Contacts and Electromechanical Components	Beijing, People's Republic of China	Professor Ji-Gao Zhang Beijing University of Posts and Telecommunications P.O. Box 109 Beijing
May 14-18	The 3rd World Conference on Neutron Radiography	Osaka, Japan	Research Reactor Institute, Kyoto University Kumatoricho, Sennan-gun, Osaka 590-04
May 16-19	The 10th International Workshop on Rare-Earth Magnets and Their Applications	Kyoto, Japan	Mr. T. Kurino c/o The Society of Non-Traditional Technology Toranomon Kotohira Kaikan Bldg, 3F 1-2-8 Toranomon Minato-ku, Tokyo 105
May 16-20	The 1st Shanghai International Symposium on Petroleum & Petrochemical Industry	Shanghai, People's Republic of China	Dr. Fan Xinfu, Senior Engineer, Chairman Steering Committee The Shanghai International Symposium on Technology of Petroleum & Petrochemical Industry
May 18-20	The 3rd Conference of Asian-Pacific Congress on Strength Evaluation	Yokohama, Japan	Professor Koji Shimizu Department of Mechanical Engineering Faculty of Engineering Kanto Gakuin University 4834 Mutsu-ura Kanazawa-ku, Yokohama 236
May 21-24	International Conference on Advanced Mechatronics	Tokyo, Japan	Japan Society of Mechanical Engineers Senshin Hokusei Bldg 2-4-9 Yoyogi Shibuya-ku, Tokyo 151
May 22-25	1989 Symposium on VLSI Technology	Kyoto, Japan	Secretariat c/o Business Center for Academic Societies Japan Conference Department 3-23-1 Hongo Bunkyo-ku, Tokyo 113
May 22-25	The 7th French-Japanese Symposium on Medicinal and Fine Chemistry  2-F30-J60	Kurashiki, Japan	French-Japanese Society for Medicinal and Fine Chemistry c/o Faculty of Pharmacology Hokkaido University Nishi-6, Kita-12 Kita-ku, Sapporo 060
May 23-26	The 5th International Conference on Hand-Arm Vibration	Kanazawa, Japan	The 5th IAV Secretariat c/o Department of Public Health School of Medicine, Kanazawa University 13-1 Takaramachi Kanazawa 920

1989			
Date	Title/Attendance	Site	Contact for Information
May 25-27	1989 Symposium on VLSI Circuits	Kyoto, Japan	Secretariat c/o Business Center for Academic Societies Japan Conference Department 3-23-1 Hongo Bunkyo-ku, Tokyo 113
May 26-27	1989 VLSI Process/Device Modeling Workshop	Suita, Osaka, Japan	Norihiko Kotani, Secretary LSI R&D Laboratory Mitsubishi Electric Corp. 4-1 Misuhara Itami 664
May 28-31	International Symposium on Large Hydraulic Machinery and Associated Equipment	Beijing, People's Republic of China	Professor Duan C.G. 14 Ya-erh Hutong Dianmen Street Beijing
May 29-31	1989 International Symposium on Multiple-Valued Logic (ISMVL-89)	Guangzhou, People's Republic of China	Dr. D.M. Miller Department of Computer Science University of Victoria P.O. Box 1700 Victoria, B.C., Canada V8W2Y2
May 29- June 2	The 2nd International Near Infrared Spectroscopy Conference	Tsukuba, Japan	Dr. Sumio Kawano National Food Research Institute Kannondai, Tsukuba 305
June 5-8	International Symposium on Thermodynamic Analysis and Improvement of Energy Systems	Beijing, People's Republic of China	Mr. Song Jialin The Chinese Society of Engineering Thermophysics P.O. Box 2706 Beijing
June 5-8	The 18th International Congress on Combustion Engines	Tianjin, People's Republic of China	Office of 18th CIMAC Congress Tianjin University Tianjin
June 6-7	IFIP WG10.2 Working Conference on the CAD Systems Using AI Techniques	Tokyo, Japan	Professor Gotaro Odawara c/o Business Center for Academic Societies Japan 3-23-1 Hongo Bunkyo-ku, Tokyo 113
June 6-9	The 1st International Symposium on Chemistry of Functional Dyes	Osaka, Japan	Professor Teiji Kitao, General Secretary of the Symposium Kinki Chemical Society, Japan 1-6-4 Utsubo-Honmachi Nishi-ku, Osaka 550
June 12-15	The XXIII Yamada Conference on Nuclear Weak Process and Nuclear Structure	Toyonaka, Japan	Professor Masato Morita 1-1 Machikaneyama-cho Toyonaka-shi, Osaka 560
June 13-18	Metallurgical/Coal/Mining Expo China '89	Shenyang, People's Republic of China	China Promotion Ltd. Room 1810 Shun Tak Centre 200 Connaught Road Hong Kong

1989

Date	Title/Attendance	Site	Contact for Information
June 20-22	The International Conference on Machinery Moving Accuracy (Theory & Measurement) ICMA (T&M)	Chongqing, People's Republic of China	Ms. Luo Sha Secretariat of ICMA (T&M) Chongqing University Chongqing, Sichuan
June 26-28	IUPAC International Symposium on Molecular Design of Functional Polymers	Seoul, Korea	Professor Sung Chul Kim Department of Chemical Engineering KAIST P.O. Box 131 Cheongyang, Seoul, Korea
June 26-30	International Symposium on Gold Geology and Exploration	Shenyang, People's Republic of China	Australasian Institute of Mining and Metallurgy Mrs. Judy Webber, Headquarter
July 2-7	The 27th International Conference on Coordination Chemistry	Gold Coast, Australia	UniQuest Limited University of Queensland St. Lucia, Queensland 4067
July 2-7	XXVII International Conference on Coordination Chemistry	Brisbane, Australia	Professor Clifford J. Hawkins Department of Chemistry University of Queensland Saint Lucia, Brisbane, Queensland 4067
July 3-5	1989 International Micro Process Conference (Micro Process '89)	Kobe, Japan	Secretariat c/o Business Center for Academic Societies Japan Conference Department 3-23-1 Hongo Bunkyo-ku, Tokyo 113
July 3-7	ICOMAT '89: The 6th International Conference for Martensitic Transformations	Sydney, Australia	ICOMAT '89 c/o M.F. Kennon Department of Metallurgy and Materials Engineering University of Wollongong P.O. Box 1144 Wollongong, NSW 2500, Australia
July 3-7	The 4th Japan-China-U.S.A. Symposium on Catalysis	Sapporo, Japan	Professor Masaru Ichikawa, Secretary Research Institute for Catalysis Hokkaido University Kita 11-jo, Nishi 10-chome Kita-ku, Sapporo 060
July 5-8	International Conference on Opto-Electronics Science and Engineering (ICOESE)	Beijing, People's Republic of China	Professor Sun Peimao Department of Precision Instruments Tsinghua University Beijing 100084
July 6-8	International Conference on Circuits and Systems (ICCAS '89)	Nanjing, People's Republic of China	Professor Wai-Kai Chen Department of Electrical Engineering and Computer Science University of Illinois at Chicago P.O. Box 4348 Chicago, IL 60680
July 7-11	The 11th International Conference on Magnetically Levitated Systems and Linear Drives (Maglev '89)	Yokohama, Japan	Professor E. Masada, Chairman Program Committee of Maglev '89 Department of Electrical Engineering University of Tokyo 7-3-1 Hongo Bunkyo-ku, Tokyo 113

1989

Date	Title/Attendance	Site	Contact for Information
July 9-14	The 4th International Conference on Scanning Tunneling Microscopy/Spectroscopy (ICSIM/STS)	Osarai, Japan	Professor Osamu Faculty of Science Tokyo Institute of Technology 2-12-1 Ohokayama Meguro-ku, Tokyo 152
July 10-14	The 4th International Symposium of Plant Biosystematics (IOPB)  30-F80-J200	Kyoto, Japan	IOPB Symposium c/o Department of Botany Faculty of Science, Kyoto University Kitashirakawa Oiwake-cho Sakyo-ku, Kyoto 606
July 10-14	The 5th World Conference on Transport Research (WCTR)	Yokohama, Japan	Professor E. Masada, Chairman Program Committee of WCTR Department of Electrical Engineering University of Tokyo 7-3-1 Hongo Bunkyo-ku, Tokyo 113
July 10-17	The 8th International Congress of Proto-Zoology	Tsukuba, Japan	Y. Nozawa Department of Biochemistry Gifu University 40 Tsukasamachi Gifu 500
July 11-14	The 1st China-Japan International Symposium on Instrumentation, Measurement and Automatic Control	Beijing, People's Republic of China	Professor Huang Jun-Qin Department of Automatic Control Beijing University of Aeronautics and Astronautics Beijing 100083
July 12-14	Topical Meeting on Solid State Lasers	Beijing, People's Republic of China	Professor Ye Peida University of Beijing Post and Telecommunications Beijing
July 17-20	The 8th International Conference on Alkali-Aggregate Reaction (8th ICAAR)	Kyoto, Japan	Dr. Toyooki Miyagawa 8th ICAAR The Society of Materials Science, Japan 1-101 Yoshida Izumidono-cho Sakyo-ku, Kyoto 606
July 17-20	The 9th International Conference on Internal Friction and Ultrasonic Attenuation in Solids (ICIFUAS 9)	Beijing, People's Republic of China	Professor T.S. Ke Laboratory of Internal Friction and Defects in Solids Institute of Solid State Physics Academia Sinica Hefei
July 17-20	Singapore International Conference on Networks: Networking - A Key to Future Communications	Singapore	IEEE Singapore Section, Computer Chapter c/o Times Conferences 19 Tanglin Road 12-02, Tanglin Shopping Center Singapore 1024, Singapore
July 18-21	The 7th International Conference on Integrated Optics and Optical Fiber Communication (IOOC '89)	Kobe, Japan	7th International Conference on Integrated Optics and Optical Fiber Communication (IOOC '89) c/o Business Center for Academic Societies Japan 3-23-1 Hongo Bunkyo-ku, Tokyo 113
July 24-26	The 2nd Microoptics Conference/The 9th Topical Meeting on Gradient-Index Imaging Systems (MOC/GRIN '89)	Tokyo, Japan	Mr. Yasuhiko Noguchi Secretariat: MOC/GRIN '89 Banda Building 1-35-5 Yoyogi Shibuya-ku, Tokyo 151

## 1989

Date	Title/Attendance	Site	Contact for Information
July 31-August 4	The 2nd International Symposium on Plasticity and Its Current Applications 20-F70-J70	Tsu, Mie, Japan	Professor Masataka Tokuda Faculty of Engineering Mie University 1515 Kamihama-cho Tsu, Mie 514
August 11-13	International Conference on Constitutive Laws for Engineering Materials	Chongqing, People's Republic of China	Associate Professor Fang Tiantong Department of Engineering Mechanics Chongqing
August 13-18	Solar Energy Congress Tokyo 1989 40-F600-J400	Tokyo, Japan	Japanese Section of International Solar Energy Society 322 San Patio 3-1-5 Takada-no-baba Shinjuku-ku, Tokyo 160
August 13-18	The 5th Congress of Federation of Asian and Oceanian Biochemists	Seoul, Korea	Biochemical Society of Korea Seoul National University San 56-1 Shillim-dong Kwanak-gu, Seoul
August 19-23	The 4th Asian Congress of Fluid Mechanics	Hong Kong	Professor N.W.M. Ko 4ACPM Secretariat c/o Department of Mechanical Engineering University of Hong Kong Pokfulam Road, Hong Kong
August 20-25	The 6th International Symposium on Novel Aromatic Compounds (ISNA-6) 20-F100-J300	Osaka, Japan	Chemical Society of Japan 1-5 Kanda-Surugadai Chiyoda-ku, Tokyo 101
August 20-25	Protein Engineering '89	Kobe, Japan	Secretariat: Protein Engineering '89 Registration Office c/o JTB Communications, Inc. New Kyoto Center Building 5F Higashi-Shirokoji Shimogyo-ku, Kyoto 600
August 20-25	The 9th International Conference on Crystal Growth (ICCG) 48-F250-J550	Sendai, Japan	Secretariat: 9th International Conference on Crystal Growth c/o Inter Group Corp. 8-5-32 Akasaka Minato-ku, Tokyo 107
August 21-26	The 14th International Conference on High Energy Accelerators	Tsukuba, Japan	Mr. Kitagawa National Laboratory for High Energy Physics 1-1 Oho Tsukuba-shi, Ibaraki 305
August 22-25	1989 International Symposium on Antennas and Propagation, Japan (ISAP '89)	Tokyo, Japan	Dr. Takashi Katagi Mitsubishi Electric Corp. 325 Kamimachiya Kamakura 247
August 22-26	The 10th International Symposium on Nuclear Quadrupole Resonance Spectroscopy	Takayama, Japan	Dr. Tetsuo Asaji The Secretary of Xth ISNQRS Department of Chemistry, PC II Faculty of Science Nagoya University Chikusa, Nagoya 464-01
August 25-28	The 7th International Conference on Composite Materials (ICCM-7)	Beijing, People's Republic of China	Tu Dezhen China Society of Aeronautics and Astronautics 67 South Street Jiao Daokou, Beijing

1989

Date	Title/Attendance	Site	Contact for Information
August 25-28	International Conference on Calorimetry and Chemical Thermodynamics (IUPAC)	Beijing, People's Republic of China	Professor Hu Ri-heng Institute of Chemistry Academia Sinica Beijing
August 26-31	The 7th International Summer School on Crystal Growth	Zao, Japan	Professor H. Komatsu ISSCG-7 Chairperson c/o Inter Group Corp. Akasaka Yamakatsu Bldg 8-5-32 Akasaka Minato-ku, Tokyo 107
August 27-31	The 3rd International Symposium on Foundation of Quantum Mechanics--In the Light of New Technology (ISQM-Tokyo '89)	Tokyo, Japan	Professor H. Ezawa Department of Physics Gakushuin University Mejiro, Toshima-ku, Tokyo 171
	NA-F50-J60		
August 27-September 1	The 5th International Symposium on Microbial Ecology (5th ISME)	Kyoto, Japan	Organizing Committee of 5th International Symposium on Microbial Ecology c/o Inter Group Corporation 8-5-32 Akasaka Minato-ku, Tokyo 107
	73-F600-J600		
August 28-30	The 1st ISSP International Symposium on the Physics and Chemistry of Organic Superconductors	Tokyo, Japan	Professor Saito The Institute for Solid State Physics University of Tokyo 7-22-1 Roppongi Minato-ku, Tokyo 106
August 28-31	International Symposium on Computational Fluid Dynamics--Nagoya, 1989 (ISCF-Nagoya 1989)	Nagoya, Japan	Professor Michiru Yasuhara Department of Aerospace Engineering Nagoya University Furo-cho, Chikusa-ku, Nagoya 464-01
August 28-31	The 5th International Symposium on Robotics Research	Tokyo, Japan	Department of Mechanical Engineering Faculty of Engineering University of Tokyo 7-3-1 Hongo Bunkyo-ku, Tokyo 113
August 28-September 1	The 11th International Conference on Magnet Technology	Tsukuba, Japan	T. Naruyama National Laboratory for High Energy Physics Oho-machi, Tsukuba-shi, Ibaraki 305
August 28-September 4	International Conference on Coordination Chemistry	Brisbane, Australia	Professor Hawkins Department of Chemistry University of QLD St. Lucia QLD 4067
August 29-31	Perpendicular Magnetic Recording Conference '89 (PMRC '89)	Tokyo, Japan	Professor Masahiko Naoe Department of Physical Electronics Tokyo Institute of Technology 2-12-1 O-okayama Meguro-ku, Tokyo 152
August 29-September 1	The 2nd International Symposium on Antennas and EM Theory (ISAE '89)	Shanghai, People's Republic of China	Mao Yukuan Xidian University 2 Taibe Road Xi'an

1989			
Date	Title/Attendance	Site	Contact for Information
August 29- September 2	Yamada Conference XXIV on Strongly Coupled Plasma Physics	Yamanashi, Japan	Professor Setsuo Ichimaru Department of Physics Faculty of Science Tokyo University 7-3-1 Hongo Bunkyo-ku, Tokyo 113
September 3-7	The 7th COMPUMAG Conference on the Computation of Electromagnetic Fields	Tokyo, Japan	T. Takagi COMPUMAG Secretariat Nuclear Engineering Research Laboratory Faculty of Engineering University of Tokyo Tokai, Ibaraki 319-11
September 4-6	IEEE International Workshop on Intelligent Robots and Systems '89 (IROS '89): The Automotive Mobile Robot and Its Application	Tsukuba, Japan	Professor Shin'ichi Yuta University of Tsukuba Institute of Information Science and Electronics Tsukuba 305
September 4-6	The 1st International Marine Biotechnology Conference	Tokyo, Japan	Professor Isao Karube, Secretary General The Japanese Society for Marine Biotechnology c/o System Research Center Co., Ltd. 505 Asahi Toranomon Building 3-18-6 Toranomon Minato-ku, Tokyo 105
September 4-8	The 7th International Conference on Liquid and Amorphous Metals  30-F120-J280	Kyoto, Japan	Professor Hirohisa Endo Department of Physics, Faculty of Science Kyoto University Oiwake-cho, Kita-Shirakawa Sakyo-ku, Kyoto 606
September 4-8	ISES Solar World Congress 1989 Kobe  65-F400-J400	Kobe, Japan	Secretariat: ISES Solar World Congress 1989 c/o International Communications, Inc. Kasho Building 2-14-9 Nihonbashi Chuo-ku, Tokyo 103
September 4-8	Beijing International Conference on High Tc Superconductivity	Beijing, People's Republic of China	Professor Z.X. Zhao Organizing Committee (BHTSC '89) The Institute of Physics Chinese Academy of Sciences P.O. Box 603 Beijing 100080
September 5-7	International Conference on Zinc and Zinc Alloy Coated Steel Sheet  20-F50-J150	Tokyo, Japan	Secretariat of GALVATECH '89 Iron and Steel Institute of Japan 1-9-4 Otemachi Chiyoda-ku, Tokyo 100
September 5-8	1989 Beijing International Symposium on Cement and Concrete (2nd BISCC)	Beijing, People's Republic of China	Mr. Zhaogi Wu, Organizing Secretary China Building Materials Academy Guanshuang, East Suburb, Beijing 100024
September 6-8	ACD&D '89 International Symposium on Advanced Computers for Dynamics and Design '89	Tsuchiura, Japan	Professor Akio Nagamatsu Chairman, The ACD&D Organizing Committee The Japan Society of Mechanical Engineers 2-4-9 Yoyogi Shibuya-ku, Tokyo 151
September 6-11	International Metal Hot Process Exhibition	Tianjin, People's Republic of China	Tianjin International Exhibition Corp. Binsui Road, Hexi District Tianjin

1989

Date	Title/Attendance	Site	Contact for Information
September 8-10	1989 International Symposium on Electromagnetic Compatibility  26-F170-J400	Nagoya, Japan	Secretariat: International Symposium on Electromagnetic Compatibility c/o Department of Information and Computer Sciences Toyohashi University of Technology 1-1 Tempaku-cho, Aza-Hibarigaoka Toyohashi, Aichi 440
September 9-14	The 2nd International Symposium on Rare Earths Spectroscopy	Changchun, People's Republic of China	Professor Su Qiang Changchun Institute of Applied Chemistry Academia Sinica Changchun 130022
September 11-12	Testing Electromagnetic Analysis Methods Workshops for Eddy Current Code Comparison  8-F30-J50	Okayama, Japan	Faculty of Engineering Okayama University 3-1-1 Tsushima-Naka Okayama 700
September 12-14	Thermtech Asia 89	Hong Kong	International Symposia and Exhibitions Ltd. Queensway House 2 Queensway Redhill, Surrey RH1 1QS, UK
September 12-16	The 2nd International Conference & Workshop on Electromagnetic Interference & Compatibility (INCEMIC)	Bangalore, India	Professor G.R. Nagabhushana High Voltage Engineering Dept. Indian Institute of Science Bangalore 560 0 12
September 17-22	International Conference on the Science and Technology of DEFECT CONTROL IN SEMICONDUCTORS-Yokohama 21st Century Forum	Yokohama, Japan	IC-STDOS c/o Lab. Physics of Crystal Defects Institute for Materials Research Tohoku University 2-1-1 Katahira, Sendai 980
September 17-22	The 40th Meeting of International Society of Electrochemistry  42-F200-J540	Kyoto, Japan	Secretariat 40th Meeting of International Society of Electrochemistry c/o Kyoto International Conference Hall Takaragaike, Sakyo-ku, Kyoto 606
September 22-25	The 3rd International Symposium on Defect Recognition and Image Processing for Research and Development of Semiconductors (DRIP III)	Tokyo, Japan	Professor Tomoya Ogawa Department of Physics Gakushuin University Mejiro, Tokyo 171
September 24-28	The 6th International Symposium on Passivity - Passivation of Metals and Semiconductors	Sapporo, Japan	Dr. Norio Satoh Faculty of Engineering Hokkaido University Nishi 8-chome, Kita 13-jo Sapporo-shi 060
September 25-28	The 5th International Conference on Numerical Ship Hydrodynamics  15-F80-J120	Hiroshima (tentative)	Faculty of Engineering Hiroshima University Shitami Saijo-cho Higashi-Hiroshima 724
September 25-29	The 16th International Symposium on Gallium Arsenide and Related Compounds	Karuizawa, Japan	Secretary: Professor T. Katoda Research Center for Advanced Science and Technology University of Tokyo 4-8-1 Komaba Meguro-ku, Tokyo 153



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Date	Title/Attendance	Site	Contact for Information
September 26-28	International Symposium on Optical Memory 1989	Kobe, Japan	Secretariat c/o Business Center for Academic Societies Japan 3-23-1 Hongo Bunkyo-ku, Tokyo 113
October 1-4	The 7th World Congress of the International Society for Artificial Organs	Sapporo, Japan	The 7th International Society for Artificial Organs c/o International Communications Inc. Kasho Bldg 2-14-9 Nihonbashi Chuo-ku, Tokyo 103
October 2-4	Today's Technology for the Mining and Metallurgical Industries  30-F300-J300	Kyoto, Japan	MMIJ/IMM Joint Symposium Office Mining and Metallurgical Institute of Japan Nogizaka Building 9-6-41 Akasaka Minato-ku, Tokyo 107
October 2-4	MMIJ/IMM Joint Symposium (Kyoto)  30-F300-J300	Kyoto, Japan	Mining and Materials Processing Institute of Japan Nogizaka Bldg 9-6-41 Akasaka Minato-ku, Tokyo 107
October 2-5	The 3rd International Conference on Computer Applications in Production and Engineering (CAPE '89)	Tokyo, Japan	Secretariat c/o Conference Department Business Center for Academic Societies Japan 3-23-1 Hongo Bunkyo-ku, Tokyo 113
October 3-5	The 10th Meeting of World Society for Stereotactic and Functional Neurosurgery  20-F200-J300	Maebashi, Japan	Department of Neurosurgery Gumma University, School of Medicine 3-39 Showa-machi Maebashi 371
October 9-12	TUBE '89 International Congress and Exhibition	Singapore	International Tube Association P.O. Box 84 Leamington Spa, Warwickshire CV32 5FX, UK
October 11-17	The 1st Asian Congress on Chemical Engineering and Biotechnology	Beijing, People's Republic of China	c/o DECHEMA Theodor-Heuss-Allee 25 P.O. Box 97 01 46 D-6000 Frankfurt-Main 97, FRG
October 15-18	The 8th International Display Research Conference - Japan Display '89  27-F200-J500	Kyoto, Japan	Secretariat of Japan Display '89 c/o Japan Convention Services, Inc. 4F, Nippon Press Center Bldg 2-2-1 Uchisaiwai-cho Chiyoda-ku, Tokyo 100
October 17-22	CIS '89 Tokyo/International Symposium on Chromatography	Tokyo, Japan	Professor Tadao Hoshino, Secretary General of CIS '89 Division of Chemotherapy Pharmaceutical Institute, School of Medicine Keio University 35 Shinanomachi Shinjuku-ku, Tokyo 160
October 18-21	The 1st ANAIC International Conference on Silicon and Tin	Kuala Lumpur, Malaysia	Professor V.G. Kumar Das Department of Chemistry University of Malaya 59100 Kuala Lumpur

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Date	Title/Attendance	Site	Contact for Information
October 22-26	International Conference on Semiconductor and Integrated Circuit Technology	Beijing, People's Republic of China	Continuing Education in Engineering University Extension University of California 2223 Fulton Street Berkeley, CA 94720
October 23-25	The 10th International Conference on Assembly Automation	Kanazawa, Japan	Conference Manager (ICAA-10) IFS Conferences 35-39 High Street, Kempston Bedford MK42 7BT England
October 23-27	International Conference on Coal Science	Tokyo, Japan	Secretariat for ICCS Coal Conversion Department New Energy Development Organization (NEDO) Sunshine 60 Building 3-1-1 Higashi-Ikebukuro Toshima-ku, Tokyo 170
October 23-28	1989 Joint International Waste Management Conference	Kyoto, Japan	Dr. A.A. Moghissi, Course Director Institute for Regulatory Science P.O. Box 7166 Alexandria, VA 22307
October 24-26	Electric Energy Conference 1989	Sydney, Australia	Conference Manager The Institution of Engineers, Australia 11 National Circuit Barton, ACT 2600
October 25-28	International Sheet Metal Working and Forming Exhibition	Hong Kong	Mack-Brooks Exhibitions Ltd. Forum Place Hatfield, Hert AL10 0RN, UK
October 26-28	ACEAN Polymer Symposium 10-F30-J30	Osaka, Japan	Institute of Scientific and Industrial Research, Osaka University 8-1 Mihogaoka Ibaraki-City, Osaka 567
October 29-November 3	International Symposium on Polymers for Microelectronics (PME '89)	Tokyo, Japan	Professor Sei-ichi Tagawa Research Center for Nuclear Science and Technology University of Tokyo Tokai, Ibaraki 319-11
November 5-9	The 7th International Conference on Solid State Ionics	Hakone, Japan	
November 5-10	The 5th International Pacific Conference on Automotive Engineering	Beijing, People's Republic of China	IPC-5 Organizing Committee c/o Society of Automotive Engineers of China 16 Fuzingsmenwai Street Beijing 100860
November 6-10	Aluminum and Magnesium	Zhengzhou, People's Republic of China	Conference Office, IMM 44 Portland Place London W1N 4BR, UK
November 7-10	International Conference on Electronic Components and Materials (ICECM '89)	Beijing, People's Republic of China	Secretariat of ICECM '89 c/o Professor Zhou Zhigang Department of Chemical Engineering Tsinghua University Beijing 100084
November 7-10	The 2nd International Symposium on the Physical and Failure Analysis of Integrated Circuits	Singapore	Secretariat IPFA Symposium Communication International Associate Pte Ltd. 450 Alexandra Road #10-00 Inchcape House, Singapore 0511

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Date	Title/Attendance	Site	Contact for Information
November 14-16	The 1989 International Symposium on Noise and Clutter Rejection in Radar and Imaging Sensors (ISNCR-89)	Kyoto, Japan	Professor Tsutomu Suzuki Department of Electronics University of Electro-Communications Chofu-shi, Tokyo 182
November 14-16	International Symposium on Exploitation and Utilization of Titaniferrous Vanadio-Magnetite	Panzhihua, People's Republic of China	STiVM Secretariat Chinese Society of Metals 46 Dongsixi Dajie Beijing 100711
November 20-23	International Conference Evaluation of Materials Performance in Severe Environments-Evaluation and Development of Materials in Civil and Marine Uses  20-F80-J120	Kobe, Japan	International Conference Secretariat Conference and Editorial Department Iron and Steel Institute of Japan 1-9-4 Otemachi Chiyoda-ku, Tokyo 100
November 20-December 1	The 1st International Symposium and Exhibition of SAMPE JAPAN CHAPTER	Makuhari, Japan	SAMPE P.O. Box 2459 Covina, CA 91722
November 22-24	Tencon 89	Bombay, India	Kirit J. Sheth, Chairman IEEE Bombay Section c/o Hakotoronics Pvt. Ltd. Dadoji Konddeo Cross Marg Bombay 400 027, India
November 27-28	Asia Vibration Conference '89	Shen Zhen, People's Republic of China	Professor Takuzo Iwatsubo Mechanical Engineering Faculty of Engineering Kobe University 1-1 Rokkodai-cho, Nada-ku Kobe-shi, Hyogo 657
November 28-December 1	1st Japan International SAMPE Symposium & Exhibition: New Materials and Processes for the Future	Chiba, Japan	1st Japan International SAMPE Symposium & Exhibition c/o The Nikkan Kogyo Shinbun, Ltd. 1-8-10 Kudan Kita Chiyoda-ku, Tokyo 102
December 11-15	The 10th Australasian Fluid Mechanics Conference	Melbourne, Australia	10AFMC c/o Professor A.E. Perry Department of Mechanical Engineering The University of Melbourne Parkville, Victoria 3052
December 11-21	The 5th International Symposium on World Trends in Science and Technology Education	Manila, Philippines	Dr. Adracion D. Ambrosio IOSTE Symposium Chairman Philippine Science High School Diliman, Quezon City 1104
1990			
Date	Title/Attendance	Site	Contact for Information
January 22-26	International Conference on Recrystallization in Metallic Materials	Wollongong, Australia	Metallurgical Society of AIME Conference Department 420 Commonwealth Drive Warrendale, PA 15086
February 4-9	The 17th International Symposium on the Chemistry of Natural Products (IUPAC)	New Delhi, India	Professor Sukh Dev Multi-Chem. Research Centre Nandesari, Baroda-39340

## 1990

Date	Title/Attendance	Site	Contact for Information
February 4-9	The 18th Australian Polymer Symposium	Bendigo, Australia	Dr. J.D. Wells Chemistry Department Bendigo CAE P.O. Box 1199 Bendigo 3550, Victoria
March 29-31	IEEE Industrial Electronics Society	Tokyo, Japan	Ohnishi Faculty of Science and Technology Keio University 3-14-1 Hiyoshi, Minato Kita-ku Yokohama-shi, Kanagawa 223
April 8-12	1990 International Topical Meeting on Optical Computing	Kobe, Japan	OC'90 Secretariat Business Center for Academic Societies Japan (BCASJ) 3-23-1 Hongo Bunkyo-ku, Tokyo 113
April 23-25	The 3rd Japan-China Joint Conference on Fluid Machinery	Osaka, Japan	Professor Yutaka Miyake Department of Mechanical Engineering Faculty of Engineering Osaka University 2-1 Yamada-Oka Suita, Osaka 565
April 23-27	Nankai Conference	Jianjin, People's Republic of China	Professor Zhao Jing-yuan Department of Physics Nankai University Jianjin
May 19-26	The 27th International Navigation Congress  62-F500-J500	Osaka, Japan	Japan Organizing Committee for 27th International Navigation Congress of PIANC c/o Port and Harbor Bureau City of Osaka 2-8-24 Chikko Minato-ku, Osaka 552
May 29- June 1	The International Conference on Manufacturing Systems and Environment - Looking Forward to the 21st Century	Tokyo, Japan	T. Nakajima The Japan Society of Mechanical Engineers Sanshin Hokusei Building 2-4-9 Yoyogi Shibuya-ku, Tokyo 151
July 1-6	The 3rd International Conference on Technology of Plasticity (3rd ICTP)	Kyoto, Japan	The Organizing Committee 3rd ICTP c/o The Japan Society for Technology of Plasticity Torikatsu Building 5-2-5 Roppongi Minato-ku, Tokyo 106
July 15-21	The 10th International Congress of Nephrology  10-F1,000-J4,000	Tokyo, Japan	Japanese Society of Nephrology c/o 2nd Department of Internal Medicine School of Medicine, Nippon University 30-1 Oyaguchi-kamicho Itabashi-ku, Tokyo 173
July 16-21	ISEC '90 International Solvent Extraction Conference	Kyoto, Japan	Conference Secretariat ISEC '90 Department of Chemistry Science University of Tokyo Kagurazaka, Shinjuku-ku, Tokyo 162
July 30- August 2	The 15th International Conference on International Association on Water Pollution Research and Control	Kyoto, Japan	Japan Society on Water Pollution Research and Control Yotsuya New Mansion 12 Honshiocho Shinjuku-ku, Tokyo 173

1990			
Date	Title/Attendance	Site	Contact for Information
August 12-17	The 15th International Carbohydrate Symposium	Yokohama, Japan	Dr. Ishido, General Secretary Faculty of Science Tokyo Institute of Technology Ookayama, Meguro-ku, Tokyo 152
August 21-29	International Congress of Mathematicians 1990  84-F1,500-J1,500	Kyoto, Japan	ICM 90 Secretariat c/o International Relations Office Research Institute for Mathematical Sciences Kyoto University Kitashirakawa Oiwake-cho Sakyo-ku, Kyoto 606
August 23-30	V International Congress of Ecology  62-F900-J1,000	Yokohama, Japan	Secretary General's Office for INTECOL 1990 c/o Institute of Environmental Science and Technology Yokohama National University 156 Tokiwadai Hodogaya-ku, Yokohama 240
September 16-22	IUMS Congress: Bacteriology and Mycology - Osaka, Japan - 1990  71-F2,000-J600	Osaka, Japan	Preliminary Committee of International Congress of Microbiology c/o JTB Creative Inc. Daiko Building 3-2-14 Umeda Kita-ku, Osaka 530
September 19-22	The 2nd World Congress on Particle Technology	Kyoto, Japan	Professor G. Jimbo Department of Chemical Engineering Nagoya University Furo-cho, Chikusa-ku, Nagoya 464-01
September 24-27	The 6th International Congress on Polymers in Concrete	Shanghai, People's Republic of China	ICPIC-90 Secretariat c/o Associate Professor Tan Muhua Institute of Materials Science and Engineering Tongji University Shanghai
September 24-28	The 3rd International Aerosol Conference	Kyoto, Japan	Professor Kanji Takahashi, General Secretary Institute of Atomic Energy Kyoto University Uji, Kyoto 611
September (tentative)	The 15th International Congress on Microbiology  57-F2,500-J2,500	Osaka, Japan	Preliminary Committee of International Congress of Microbiology c/o JTB Creative Inc. Daiko Building 3-2-14 Umeda Kita-ku, Osaka 530
October 15-19	The 4th International Symposium on Marine Engineering (ISME KOBE '90)	Kobe, Japan	The Marine Engineering Society in Japan Hibiya Osaka 2nd Bldg 1-2-2 Uchisaiwai-cho Chiyoda-ku, Tokyo 100
October 21-26	The 6th International Iron and Steel Congress  50-F300-J500	Nagoya, Japan	International Conference Department Iron and Steel Institute of Japan 3F, Keidanren Kaikan 1-9-4 Otemachi Chiyoda-ku, Tokyo 100
1990 (tentative)	Chemeca 1990 Applied Thermodynamics	New Zealand	Conference Manager The Institution of Engineers, Australia 11 National Circuit Barton, ACT 2600

1991			
Date	Title/Attendance	Site	Contact for Information
February 7-12	The 10th International Conference on Offshore Mechanics and Arctic Engineering	Seoul, Korea	Korea Cmt for Ocean Resources and Engineering Dong-A University 840 Sahagu Pusan, Korea
February 10-15	POLYMER '91: International Symposium on Polymer Materials	Melbourne, Australia	Dr. G.B. Guise P.O. Box 224 Belmont, VIC 3216, Australia
July 24-30	The 17th International Conference on the Physics of Electronic and Atomic Collisions	Brisbane, Australia	Dr. W.R. Newell Department of Physics University College of London Gower Street London WC1E 6BT UK
July 29	The 6th Conference of International Congress on Mechanical Behavior of Materials	Kyoto, Japan	Professor Tatsuo Inoue Faculty of Engineering Kyoto University Yoshida-Honmachi Sakyo-ku, Kyoto 606
August 25-31	International Congress on Analytical Science-1991 (ICAS '91)	Chiba, Japan	The Japan Society for Analytical Chemistry Rm 304 Gotanda Sun Heights 1-26-2 Nishi Gotanda Shinagawa-ku, Tokyo 141
August (tentative)	International Congress on Medical Physics  45-F600-J900	Kyoto, Japan	National Institute of Radiological Science 4-9-1 Anagawa Chiba 260
August (tentative)	The 16th International Conference on Medical and Biological Engineering (ICMBE)	Kyoto, Japan (tentative)	Japan Society of Medical Electronics and Biological Engineering 2-4-16 Yoyogi Bunkyo-ku, Tokyo 113
1992			
Date	Title/Attendance	Site	Contact for Information
October 26-30	The 14th International Switching Symposium (ISS '92)  60-F1,200-J800	Yokohama, Japan	NTT Communication Switching Laboratories 3-9-11 Midori-cho Musashino-shi, Tokyo 180
Autumn	XIVth International Switching Symposium (ISS '92)	(to be decided)	Institute of Electronics, Information and Communication Engineers (IEICE) Kikai Shinko Kaikan 3-5-8 Shiba-koen Minato-ku, Tokyo 105
1993			
Date	Title/Attendance	Site	Contact for Information
1993 (tentative)	International Federation of Automatic Control Congress	Sydney, Australia	Conference Manager The Institution of Engineers, Australia 11 National Circuit Barton, ACT 2600

1994			
Date	Title/Attendance	Site	Contact for Information
Tentative	XXX International Conference on Coordination Chemistry	Kyoto, Japan	Professor Hitoshi Ohtaki Coordination Chemistry Laboratories Institute for Molecular Science Myodaiji-cho, Okazaki 444

*Yuko Ushino is a technical information specialist for ONR Far East. She received a B.S. degree from Brigham Young University at Provo, Utah.*

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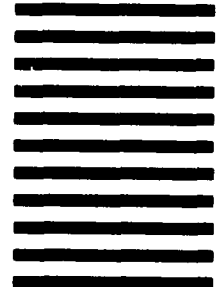


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